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ADVANCED
PHYSIOGRAPHY

STAGE II.

BY

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PREFACE

THIS work has been prepared at the request of the publishers and many teachers, as a supplement to the elementary treatise on the same subject written by me about three years ago. In the present book, as in the earlier one, I have put upon Physiography the liberal interpretation given to it in the South Kensington Syllabus, in which it includes the main facts and principles of elementary physics, geology, oceanography, meteorology, and astronomy. Physiography is thus pre-eminently a science of observation and experiment, and it is as such that I have endeavoured to treat of it in the following pages.

A large number of photographs and other illustrations appear in the book by the kind consent of various authors and publishers. Under each of the figures referred to I have stated its authorship or the source from which it has been borrowed—a practice not so common as it deserves to be.

Fully half of the illustrations have been specially drawn for the book, and are for the most part diagrams intended solely to elucidate the text, or to illustrate the essential points of an experiment. They are such drawings as are likely to be made by the student afterwards in planning apparatus for an experiment or in carrying out any investigation.

I desire to acknowledge the invaluable help I received from Mr. J. W. Butters, M.A , B.Sc., F.R.S.E., Mr. J. B. Clark, M.A., F.R.S.E., Mr. Archibald Milne, M.A., and Mr. J. Rennie, B.Sc., who have revised the proofs, and made many corrections and important suggestions on them.

ALEX. MORGAN.

EDINBURGH,
May 27th, 1901

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ADVANCED PHYSIOGRAPHY

CHAPTER I.

SOME OF THE PROPERTIES OF MATTER.

In physiography we have to study, and as far as possible explain, the chief phenomena of Nature. But the essential basis—the substratum—of these phenomena is matter, and hence at the outset the question naturally arises, *What is matter?* To answer this question is absolutely impossible, for we do not know what the precise nature and ultimate structure of matter are. Our inability, however, to define matter is no obstacle to our study of Nature, in which we have to deal only with the properties of matter, and these we know by direct observation and experiment and by reasoning upon the data supplied by them. We assume that the student has become familiar with many of those properties in his study of elementary physiography, and that it is only necessary now to extend and supplement that knowledge.

Matter occupies Space.—This is one of the essential properties of matter, and is frequently given as a so-called definition of it. Again, no two portions of matter can occupy the same portion of space at the same time. This property is known as the *impenetrability of matter*. For example, when a stone sinks in water it displaces its own bulk of water. Or when a nail is driven into wood, it does not really penetrate into the wood; it forces some of the wood-fibres out of the way and takes their place.

Divisibility of Matter.—A body of matter may be divided or broken into parts similar in constitution to the body. For instance, a piece of table salt (sodium chloride) may be ground into smaller and smaller parts, and the question naturally arises, Is there a limit to its divisibility without changing its character? Evidently there is, for we could, by

suitable processes, ultimately reach a point at which the substance is no longer salt but is broken up into sodium and chlorine. The facts of physics, chemistry, and mineralogy all point to the conclusion that matter is made up of exceedingly minute indivisible particles separated by exceedingly small spaces, and *these smallest separable particles of a substance which cannot be divided without changing it into other kinds of matter are called molecules.* It must be clearly understood that molecules are far too small ever to become visible; indeed, it is calculated that the smallest speck of matter that can be seen contains more than fifty millions of them.

Gold, for example, can be made into a film less than $\frac{1}{4000000}$ of an inch thick, and in this thickness there are many molecules side by side. Even ordinary gold-leaf has a thickness of only about $\frac{1}{300000}$ of an inch, and in a square inch of such a leaf there are about 90,000 million molecules.

The study of chemistry has shown that each molecule must contain at least two, but probably many, parts called *atoms.* This word signifies literally "that which cannot be cut" or divided, and *atoms are so called because they cannot exist separately, but only in groups called molecules.* Every molecule of water, for instance, contains two atoms of hydrogen and one of oxygen.

Porosity of Matter.

EXPT. 1.—Drop a piece of chalk of known weight into water and observe what happens. Weigh the chalk again after it is removed from the water.

EXPT. 2.—Put some mercury into a bag made of chamois leather. Note the result of squeezing the mercury by twisting the mouth of the bag.

EXPT. 3.—Into a graduated glass put, say, 50 c.c. of pure alcohol, and add gently to it 50 c.c. of water. Close the open end of the glass with the hand and invert it several times, and note the resulting volume, and anything seen to happen during the mixing.

Francis Bacon, in 1640, tried to compress water by enclosing it in a spherical shell of lead, which he hammered, but the water exuded through the lead and stood on the outside of it like beads of perspiration. Since then the experiment has been repeated with a silver shell, and with the same result. In order to prevent, if possible, the escape of the water, the silver shell was thickly gilded, but the water came through the gold also.

From such experiments we conclude that there are vacant spaces between the individual molecules of a body, and probably also between the atoms that form the molecules. These spaces are called the interstices or *pores.* In the first experiment, the bubbles of gas seen rising from the chalk were due to the water driving the air out of the pores. In the next case the mercury passed through the pores of the leather, and

indeed this is the ordinary way of filtering mercury. Finally, the mixture of alcohol and water, instead of being 100 c.c., was only about 97 c.c., showing that the molecules of alcohol and water are able to a certain extent to interpenetrate into the spaces between the molecules. The minute bubbles seen to rise during the mixing were owing to the alcohol having partly penetrated into the intramolecular spaces of the water and expelled the air, and to the water similarly penetrating into the spaces between the molecules of alcohol.

When we say that all bodies are porous, we do not refer merely to bodies having visible pores, such as the skin of the human body, or a piece of blotting-paper or cork, but also to those, such as lead, silver, gold, etc., whose pores cannot be rendered visible even with a microscope. As yet glassy substances have not been experimentally proved to be porous, but this is doubtless because we have not fallen upon the proper method.

Elasticity.

1. *Definition of Elasticity.*—When a body, after being altered in shape or volume by a force, returns wholly or partially to its original shape or volume when the force is removed, it is said to be elastic.

EXPT. 4.—Slightly cover a flat smooth surface of slate or marble with a sticky colouring substance, such as oil and lycopodium powder. Press a glass solitaire-ball or an ivory billiard-ball upon this, and observe the size of dot made. Then allow the ball to fall from a height of 3 or 4 feet. Observe that the dot is larger than before, and that the ball is still perfectly round, but that there is a circular blot upon it. These things show that the ball was momentarily flattened by the blow, and that the rebound was due to the ball regaining its original shape. Hence glass or ivory is elastic. Now allow a leaden bullet to fall; the flattening remains, therefore lead is inelastic, or rather its elasticity is very small. Similarly, clay and putty would be found to be almost inelastic so far as shape is concerned.

DEFINITION.—*The elasticity of a body is that property by virtue of which it resists an alteration of form or volume, and recovers its original form or volume when the force is removed.* The two properties, therefore, of *resistance* and of *restitution or recovery* must be possessed by a body before it can be said to be elastic. Ordinary indiarubber, for example, is elastic, not because it offers little resistance to a stretching force, but because it can recover itself when the force is removed.

Elasticity is a most important property, for we shall find that it is by means of it that sound and light and other forms of wave-motion are propagated.

2. *Different Kinds of Elasticity.*—From what has just been

said, it is evident that there are two kinds of elasticity, viz. *elasticity of volume* and *elasticity of form*, and in the latter case the change of shape may be produced in many different ways, but the most important are (*a*) pulling, (*b*) torsion or twisting, and (*c*) bending.

Solids possess elasticity both of volume and form, for they resist having either of these altered; liquids and gases have elasticity of volume but very small elasticity of form, for they offer little resistance to a change of shape, always taking the shape of the vessel containing them.

3. *Magnitude of the Elasticity of a Body.*—When a body is changed in volume or shape it is said to be strained, and the change is called a *strain;* also, when a body is strained, forces are called into play (by the displacement of the particles relatively to each other) resisting the strain and tending to restore the body to its unstrained state. This system of internal forces produced by the strain is called a *stress.*

Every substance has its own particular elasticity, called the *modulus or coefficient of elasticity* of the substance. The elasticity of a substance is measured by the ratio of the stress to the strain that called it into play, or—

$$\text{Coefficient of elasticity of a substance} = \frac{\text{stress}}{\text{strain}}.$$

Moreover, a body may offer a slight resistance to change of form but a great resistance to a change of volume, or *vice versâ.* Hence each kind of substance has its own coefficient of elasticity of volume and of form (*i.e.* of extension, of torsion, and of bending).

In ordinary language we call substances like indiarubber very elastic because they yield readily to force, but in scientific language, as we have just seen, elasticity refers not to yielding to force, but to resisting change of shape or volume, as the case may be.

4. *Limit of Elasticity.*—If the force applied to a body be so great as to displace its molecules beyond a certain limit, it loses its power of returning to its original shape or volume when the force is withdrawn. This limit is called the *limit of elasticity of the substance.* In sprains, for example, the limit of elasticity of the tendons has been exceeded. A knowledge of this limit for various materials is essential to engineers and others, for in structures it must not be exceeded nor even too nearly approached. Some solids (*e.g.* indiarubber) have a wide

limit of elasticity, others (*e.g.* glass) have a narrow limit, but for stresses within its limit of elasticity each substance is perfectly elastic. Gases and liquids have no such limit, their elasticity being perfect under all pressures, for they return to exactly the original volume when the stress is removed.

Elasticity of Volume.—From what has just been explained, we know that—

$$\text{Coefficient of elasticity of volume} = \frac{\text{stress}}{\text{strain}}.$$

The stress is estimated by the amount of pressure applied to each unit of surface of the body to compress it, and the strain is measured by the diminution of bulk produced per unit of volume; therefore—

$$\text{Coefficient of elasticity of volume} = \frac{\text{pressure per unit of area}}{\text{resulting compression per unit of volume}}.$$

If P be the pressure per unit of surface, V the original volume and v the change of volume, so that $\frac{v}{V}$ is the change of volume per unit of volume, then the elasticity of volume is determined by the expression—

$$\text{Coefficient of elasticity of volume} = \frac{P}{\frac{v}{V}} = \frac{PV}{v}.$$

The value of this coefficient for several common substances is given in the table on p. 11.

Compressibility *is the property of a body by virtue of which its volume can be diminished by pressure.* It is a necessary consequence of porosity, for if there be vacant spaces between the molecules of a body it must be possible to force the latter closer together by using sufficiently great pressure. The greater the force required the less the compressibility of the body, so that *the compressibility of a substance is the inverse of its volume-elasticity, and is therefore equal to* $\frac{v}{PV}$.

Matter is most compressible when in the gaseous state; solids have, as a rule, slight compressibility, and liquids are almost incompressible.

1. *Compressibility of gases.*

Expt. 5.—To show the compressibility of gases, use what is called a *fire-syringe*. This is a strong glass tube closed at one end, and provided

with a tight-fitting piston (Fig. 1). On pressing in the piston the air in the tube is compressed, and as the diminution of volume goes on the force exerted on the piston has to be gradually increased. Now remove this force, and the elasticity of the enclosed air drives back the piston to its original position.

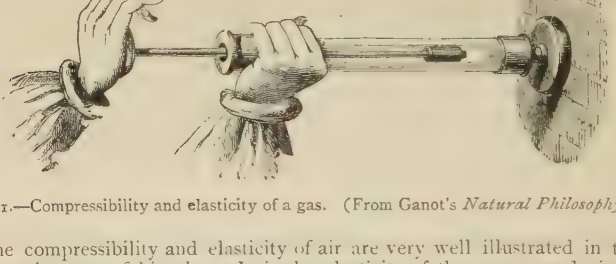


FIG. 1.—Compressibility and elasticity of a gas. (From Ganot's *Natural Philosophy*.)

The compressibility and elasticity of air are very well illustrated in the pneumatic tyres of bicycles. It is the elasticity of the compressed air in them that makes these tyres so much more comfortable than the old solid rubber ones.

It is important to know the relation between the change of volume of a gas and the pressure producing the change. This was first determined by Boyle by a method which we cannot give here, but which is described in the *Elementary Physiography treated Experimentally*, p. 143. The result is now known as BOYLE'S LAW,[1] viz. *the volume of a gas is inversely proportional to the pressure;* i.e. by doubling the pressure on a gas we halve its volume, and by halving the pressure we double the volume, and so on. From this it follows that the *volume-elasticity of a gas is directly proportional to the pressure, and the compressibility of a gas, being the reciprocal of its volume-elasticity, is inversely proportional to the pressure on the gas.*

2. The *compressibility of liquids* is so slight that for a long time they were regarded as completely incompressible. We have already referred to Bacon's failure to compress water by hammering a leaden shell enclosing it. Early in the nineteenth century there was invented an instrument called the piezometer (Gr. *piezo*, "I compress;" *metron*, "a measure"), by which it is now an easy matter to observe and measure the compressibility of a liquid.

As an example of the small compressibility of liquids, we

[1] It is generally called Mariotte's Law on the Continent; but Mariotte published his *Discours de la Nature de l'Air* in 1676, whereas Boyle published his *Defence of the Doctrine of the Spring and Weight in Air* in 1662.

may state that experiments show that a pressure of one atmosphere (14·73 lbs. per square inch) reduces the volume of water by only 0·00005 of its amount, while the same pressure reduces air to 0·5 of its original volume; that is, the compressibility of water is only $\frac{1}{10000}$ that of air (hence the elasticity of water is 10,000 times that of air, for 10,000 times as great a force would be required to diminish its volume by the same fraction).

3. The *compressibility of solids* is determined in a somewhat similar way. Great differences are shown among solids with respect to this property, wood, cork, paper, and cloth being amongst the most compressible.

The compressibility of each substance in the table on p. 11 can be found by dividing unity by the volume-elasticity there given.

Rigidity, or Elasticity of Shape.—A body is said to be rigid if, when stress is applied to it, it experiences no strain—that is, no change of shape or volume. But in simple rigidity change of shape alone is considered, the volume being supposed to remain constant, hence *simple rigidity is just elasticity of shape, or the resistance a body offers to change of form, assuming its volume to remain constant.* No substance is perfectly rigid—that is, suffers no deformation if we act for a long time on a mass of it however small (such as thin wire), by a force however great. In practice, a body is said to be rigid if the ratio $\frac{\text{stress}}{\text{strain}}$ be very large. In this sense solids may be rigid, as, *e.g.*, iron, or flexible, as, *e.g.*, indiarubber and thread. Neither liquids nor gases possess rigidity. It will be seen, from the table on p. 11, that steel is one of the most rigid substances, its coefficient of simple rigidity being, indeed, more than 5000 tons per square inch.

A strain which consists of a change of form only, without change of volume, is called a *shearing strain*, or a *shear*, and the force which produces it is called a *shearing stress*, and the elasticity of shape, or simple rigidity, of a substance is given by the expression—

$$\text{Coefficient of simple rigidity} = \frac{\text{shearing stress}}{\text{shearing strain}}$$

the shearing stress and strain being measured as explained below.

To illustrate such a strain, consider ABCD in Fig. 2 to represent a pack of cards. By applying a slight force in the direction AD, we can

deform the pack by sliding each card upon the one below it a small amount, as A′BCD′. Since the area of the base of the pile and the height remain unaltered, the volume has not been changed.

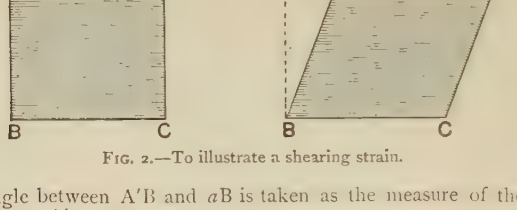


FIG. 2.—To illustrate a shearing strain.

The angle between A′B and aB is taken as the measure of the strain; and the ratio $\frac{aA'}{aB}$ of the displacement aA′ to the depth aB is taken as the measure of the stress, for if aA′ were doubled, then the force resisting the strain would be doubled, and if the height aB of the pile were doubled, it would only be half as difficult to produce the same displacement.

Longitudinal Elasticity (Young's Modulus).

EXPT. 6.—Let an indiarubber cord about 50 cms. long be suspended, and carry a very light scale-pan at its lower end (Fig. 3). At two parts A and B of the cord, about say 40 cms. apart, let two small pins be thrust so that the points project a little through the rubber. Measure the distance between A and B when the rubber is stretched by the weight of the pan only. Then let a weight of, say, 50 grams be placed in the pan, and measure the distance between the pin-points at A′ and B′. The difference between A′B′ and AB is the *longitudinal strain* of AB, and the mutual pull between the weight and the hook is the *longitudinal stress;* it is equal to the weight. Repeat the experiment, using double the weight, treble the weight, and so on. Go over the experiment again, using a thicker band of indiarubber.

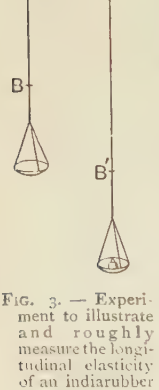


FIG. 3. — Experiment to illustrate and roughly measure the longitudinal elasticity of an indiarubber band.

From experiments of this kind, in which, however, the changes of length are measured with much more care than we have indicated, it is found that, within the limits of elasticity, the amount of elongation of a cord, wire, or rod depends on four things—

(1) *The material used.*

(2) *The stretching force;* the elongation is directly proportional to the stretching force.

(3) *The length;* the elongation is directly proportional to the length when unstretched.

(4) *The area of cross-section;* the elongation is inversely proportional to the sectional area.

The ratio of the longitudinal stress to the elongation produced is called *Young's Modulus* (or simply the "modulus of elasticity," but this expression is apt to lead to confusion, since elasticity may, as we have seen, be estimated in so many ways). Now, if L be the original length, and l the increase of length of the wire, then the strain or increase of length per unit length is $\frac{l}{L}$; and if W be the stretching weight, and A the area of cross-section of the wire, then the stress or stretching force per unit area is $\frac{W}{A}$. Hence—

$$\text{Young's modulus} = \frac{\text{longitudinal stress}}{\text{longitudinal strain}} = \frac{\text{stretching force per unit area}}{\text{resulting elongation per unit of length}} = \frac{\frac{W}{A}}{\frac{l}{L}} = \frac{WL}{Al}.$$

The numerical value of Young's modulus depends, therefore, on the units of force and of length used. For example, if the unit of force is the weight of 1 lb., and the unit of length the inch, then Young's modulus for wrought iron is 25 millions—that is, a bar of wrought iron is elongated $\frac{1}{25000000}$ part by a stretching force of 1 lb. per square inch. Young's modulus for some common substances is given on p. 11 in C.G.S. units.

Torsional Elasticity and the Laws of Torsion.—We have just been studying extension, or the change of form produced by a stress acting longitudinally, *i.e.* parallel to the axis of the cylindrical rod or wire. We shall now briefly consider torsion, or the change of form produced by a stress acting tangentially, *i.e.* at right angles to the axis of the wire. Imagine the cylindrical rod or wire to be made up of a series of transverse slices, as represented in Fig. 4. Then, if the lower end BC were clamped, and a twisting force applied to the upper end AD, as indicated by the arrow, each slice would slide round on the one below it; and we see that in the torsion the change of form consists in the parallel transverse layers rotating round the axis of the cylinder, and that each layer turns through an angle proportional to its distance from the fixed end.

To study the laws of torsion, an apparatus called the torsion balance is used. It consists essentially of a fine wire of the substance to be studied, suspended as shown in Fig. 5, supporting a weight, B, and also a light pointer which moves over

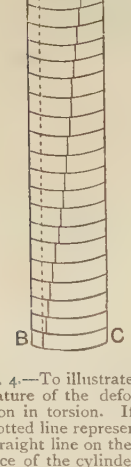


FIG. 4.—To illustrate the nature of the deformation in torsion. If the dotted line represents a straight line on the surface of the cylinder before the twisting takes place, it becomes like the broken line after the twisting.

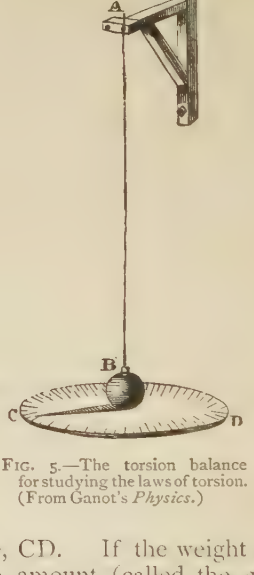


FIG. 5.—The torsion balance for studying the laws of torsion. (From Ganot's *Physics*.)

a fixed horizontal graduated circle, CD. If the weight and pointer are twisted round a certain amount (called the *angle of torsion*), then the wire, owing to its elasticity, resists the torsion, and the force with which it does so is called the *force resisting torsion*, and if the weight is then released the pointer will oscillate like a pendulum. Coulomb, with this apparatus, found the laws of torsion for deflections within the limit of elasticity to be—

(1) *All oscillations are isochronous* (Gr. *isos*, "equal;" *chronos*, "time"), that is, take place in exactly the same time whether the angle of torsion be large or small.

(2) *The force resisting torsion is proportional to the angle of torsion*, i.e. if the wire were twisted, say, 180°, then the force tending to bring it back is only one-half of what it would be if it were twisted right round (360°), and is double what it would be if it were twisted only through a right angle.

(3) *The force resisting torsion is inversely proportional to the length of the wire*, i.e. if the wire were doubled in length, the resistance to torsion would be halved.

(4) *The force resisting torsion is proportional to the fourth power of the diameter of the wire* (*or rod*), i.e. if the diameter of the wire were doubled, the force of resistance for any given angle of torsion would be 2^4 or 16 times as great as before; and if the diameter were trebled, the force would be 3^4, or 81 times as great as before, and so on.

If F be the force resisting torsion, l the length and r the radius of the wire, and α the angle of torsion, then all the above laws of torsion are expressed by the equation—

$$F = c\frac{r^4\alpha}{l},$$

where c is a constant depending on the material of which the wire consists, and is called the *coefficient of torsional rigidity of the substance.* It will be seen from Fig. 4 that the distortion is of the nature of a shear, hence there is a relation between the coefficient of torsional elasticity and the coefficient of simple rigidity given below, and this relation is $c = \frac{\pi}{2}n$, where n is the coefficient of simple rigidity. Therefore—

$$F = \frac{\pi n r^4 \alpha}{2l}.$$

These laws are of great practical importance, as they enable us to measure, for example, the density of the earth and the earth's magnetic forces.

We give for reference the values in Everett's *Physical Constants* of the various coefficients for a few common substances. They are expressed in the C.G.S. system, that is, in grams per square centimetre :—

COEFFICIENTS OF ELASTICITY.

Substance.	Coefficient of volume elasticity.	Coefficient of simple rigidity.	Young's modulus.
Distilled water	$0{\cdot}222 \times 10^{11}$	—	—
Flint glass .	3·47 to 4·15 ,,	$2{\cdot}35$ to $2{\cdot}40 \times 10^{11}$	$5{\cdot}74$ to $6{\cdot}03 \times 10^{11}$
Brass . . .	10·02 to 10·85 ,,	3·44 to 4·03 ,,	9·48 to 11·20 ,,
Steel . . .	18·41 ,,	8·19 ,,	20·20 to 24·50 ,,
Wrought iron	14·56 ,,	7·69 ,,	19·63 ,,
Cast iron . .	9·64 ,,	5·32 ,,	13·49 ,,
Copper . . .	16·84 ,,	4·40 to 4·47 ,,	11·72 to 12·34 ,,

Questions.

1. If bodies are built up of molecules, why can they be made smaller by pressure, and how can they contract when cooled?

2. Explain the terms "elasticity," "limit of elasticity," and "coefficient of elasticity." How is elasticity measured?

3. What are the different kinds of elasticity, and how is each kind estimated? Why do you say that steel is more elastic than rubber?

4. Illustrate the meaning of the term "compressibility." How has it been shown that water is compressible?

5. What is meant by the term "rigidity," and how is it measured? How does this property enable a solid to be distinguished from a fluid?

6. Explain the expression "coefficient of rigidity." Name some substances in which this coefficient is high, and some in which it is low.

7. Under what conditions would a solid be said to be perfectly rigid?

8. Describe an experiment by which you could determine the modulus of elasticity of indiarubber or copper.

9. How would you prove that the elongation of a cord of indiarubber depends upon the stretching force, the length of the cord, and the thickness?

10. What do you understand by torsion? Describe an experiment to illustrate it. How would you show that, whatever the amplitude of the oscillations of a weight attached to a twisted wire may be, they are always performed in the same time?

11. Young's modulus for a copper wire being 17,000,000 lbs. per square inch, find the elongation of a wire 15 feet long, whose section is 0·01 of a square inch, under a tension of 85 lbs. per square inch.

The answers to numerical questions are given at the end of the book.

CHAPTER II.

FORCE, WORK, AND ENERGY.

Definition of Force and of the Units of Force.—The student will have already learned, in connection with his elementary study of the subject, that *force is what changes, or tends to change, a body's state of rest or of uniform motion in a straight line.* Also, he will remember the "second law of motion" (see *Elementary Physiography*, p. 14)—that change of momentum (mass multiplied by velocity) is proportional to the force that causes it. This law provides us with a definition of unit force, for according to it—

Force $\propto$ [1] rate of change of momentum (M $\times$ V)
$\propto$ M $\times$ rate of change of V (keeping the mass constant)
$\propto$ M $\times$ *a* (since acceleration is the rate of change of velocity),
or F = M*a*, if we take the proper units of force, mass, and space.

From this we see that if M and *a* be each equal to 1, then F is also 1, or *the unit of force is such that if it acts on unit mass it will produce unit acceleration.* We may mention the following units of force:—

1. The F.P.S. (foot-pound-second) unit of force is called THE POUNDAL. *This is the force which, acting on a mass of one pound, produces an acceleration of one foot per second each second.*

2. The C.G.S. (centimetre-gram-second) unit of force is called THE DYNE. *This is the force which, acting on a mass of one gram, produces an acceleration of one centimetre per second each second.*

3. There is a third unit of force frequently used by engineers and others, viz. THE POUND WEIGHT, *which is the force with which the earth attracts a mass of one pound.* But this force varies with locality, and is therefore not a suitable unit for scientific purposes.

Each second the force of gravity increases the velocity of a falling body (whatever its mass may be) about 32 feet per second. This is usually denoted by *g*. But the earth attracts a mass of one pound with a force of one pound-weight, and if the mass fall from rest it will, because of this

[1] Of course the reader will know that this symbol means "is proportional to."

attraction, have at the end of one second a velocity of 32 *feet per second*, whereas a poundal acting on a mass of one pound for one second gives it a velocity of only *one foot per second*, hence—

one pound-weight = 32 *poundals*, or *g poundals*.

The poundal and the dyne are called *absolute* units of force, because they do not vary from place to place, whereas the gravitation unit of force—the pound-weight—has different values in different latitudes.

Work and how it is measured.—When a force acts upon a body and makes it move in the direction of the force, that force is said to *do work* on the body, and the amount of work done is measured by the product of F, the force acting, into S, the space through which the body has been moved in the direction of action of the force. That is—

$$\text{Work} = F \times S.$$

For example, suppose that the steam in the cylinder of a steam-engine exerts on the piston, whose cross-section has an area of 40 square inches, a pressure equal to the weight of 60 lbs. per square inch, and that the piston moves 30 inches. Then the total pressure on the piston is 60 lbs.-weight × 40, or 2400 lbs.-weight, and at each stroke of the piston—

The work done by the force = 2400 lbs.-weight × 2½ feet
= 6000 *foot-pounds*.

Conversely, when a force F acts upon a body, and the body moves through a distance S in the direction opposed to the force, then work is not said to be done *by* the force but *against* it, the work done being measured as before by F × S, the product of the force resisted into the space traversed.

Thus, in lifting a mass of 20 lbs. 4 feet against the force of attraction between the earth and the body—

The work done against the force of gravity = F × S
= 20 lbs.-weight × 4 feet
= 80 *foot-pounds*.

Hence we get the following definition of work and its measurement: *When a force acting on a body makes the point at which it is applied move in the direction in which the force acts, work is said to be done by the force, and when the body moves in the opposite direction to the force, work is said to be done against the force, and in every case the work is measured by the product of the force F and the space S through which it acts, or work = FS.*

The Units of Work.—Since work = F × S, if F × S = 1, we have the unit of work. This is the case when F = 1 and

S = 1; that is, *the unit of work is the work done by a unit of force in acting through a unit of distance.* According to the units of force and space employed, we get the following units of work :—

1. The F.P.S. unit of work (or the British absolute unit of work) is called THE FOOT-POUNDAL. *It is the work done by a force of one poundal acting through a distance of one foot.*

2. The C.G.S. unit of work (or the French absolute unit of work) is called THE ERG. *It is the work done by a force of one dyne acting through a distance of one centimetre.*

3. The British gravitation unit of work is called THE FOOT-POUND. *It is the work done in raising one pound vertically through a distance of one foot against the force of gravity.* This is a variable unit depending on latitude, and since the weight of a pound equals about 32 poundals—

$$\text{One foot-pound} = 32 \text{ foot-poundals} = g \text{ foot-poundals.}$$

Activity, Power, or Rate of doing Work.—One man may be able to do the same amount of work faster than another, and in that case we would say that the working *power* or *activity* of the first is greater than that of the second. Again, a man takes longer to do a certain amount of work than a steam-engine would take—that is, the power or activity of the two is not the same. *The rate of doing work is called the power or activity of the agent.* British engineers use a unit of the rate of doing work called a HORSE-POWER (H.P.), *a horse-power being the rate of doing* 33,000 *foot-pounds of work per minute.* It was so called by James Watt, the engineer, because he estimated this to be the amount of work a horse can do per minute. A man can, for about four hours, work at the rate of about $\frac{1}{5}$ H.P., but for a very short time he can work at a considerably greater rate, *e.g.* running up a stair.

Energy, or the Capacity of doing Work.—The student should at this stage revise what he has already learnt regarding energy (see *Elementary Physiography*, pp. 41–49). He will have learned that the name "energy" is applied to the capacity which a body may, for any reason, possess of doing work, and that it has two fundamental forms, namely, *kinetic energy* or the capacity that a moving body has of doing work in virtue of its motion; and *potential energy* or the capacity that a body has of doing work because of its position or any circumstance other than motion. He will be familiar, too, with the fact that by energy of motion we do not merely refer to energy of visible motion, such as is possessed by a hammer in

its descent, but also to the invisible vibrations that produce sound, light, heat, electricity, etc. He will have observed that in most cases potential energy requires some "liberating force," as it is called, to start its transformation into kinetic energy, and so into work. Thus the potential energy stored up in the compressed air in an air-gun cannot do the work of propelling the bullet until it is liberated by some one pulling the trigger; and, similarly, the potential energy of fuel is unable to do the work of driving machinery until the chemical action is started by the application of heat.

Measurement of Kinetic Energy.—We measure the kinetic energy of a moving body by finding the amount of work it would do if all its energy of motion were converted into work. But Work equals FS, whereas the quantity of work a body is capable of doing in virtue of its motion depends obviously on its mass and its velocity. Hence we must find what F and S are in terms of mass and velocity. This can be found as follows:—

If a be the acceleration or increase in the velocity produced by the force each second, then, starting from zero velocity—

The velocity at the end of 1 second will be a feet per second.
" " " 2 seconds " $2a$ " "
" " " 3 " " $3a$ " "
" " " t " " ta " "

or $V = ta$, and therefore $a = \frac{V}{t}$.

But if the velocity of a body at the beginning is 0, and at the end is V, then it is obvious that its average velocity during the period was $\frac{1}{2}V$. Also—

Space described = average velocity × time
that is, $S = \frac{1}{2}Vt$.

Finally—

$$\begin{aligned} \text{Kinetic energy} &= \text{work the body is capable of doing} \\ &= F \times S \\ &= Ma \times S \\ &= M\frac{V}{t} \times \tfrac{1}{2}Vt \\ &= \tfrac{1}{2}MV^2. \end{aligned}$$

Wherefore *the kinetic energy of a body is measured by half the product of its mass into the square of its velocity*. It must be carefully noted that, since energy is transformable into work, it is expressed in the same units. Therefore, if M be the mass of the body in pounds, and V its velocity in feet per second, then

$\frac{1}{2}MV^2$ gives the kinetic energy of the body in *foot-poundals*, and $\frac{MV^2}{2g}$ is the kinetic energy in *foot-pounds*. If the mass be expressed in grams, and the velocity in centimetres per second, then $\frac{1}{2}MV^2$ gives the kinetic energy in *ergs*.

For instance, the kinetic energy of a projectile weighing 100 lbs. and moving at the rate of 500 yards per second is $\frac{1}{2} \times 100 \times (1500)^2 = 112,500,000$ *foot-poundals*. The number of *foot-pounds* would be this divided by 32.

Measurement of Potential Energy.—Potential energy implies previous expenditure of work to put the body into its position of advantage, and the quantity of potential energy is just equal to the work that has been done. Therefore—

Potential energy of a body at a height = work done in raising it
= force overcome × distance
= $Mg \times S$ (for the weight of a mass M is Mg).

Hence the energy stored up in an elevated body depends on its mass, the local accelerative force of gravity, and the height of the body above the earth's surface.

For example, the potential energy of a steam-hammer weighing a quarter of a ton and raised 10 yards = $MgS = \frac{1}{4}$ of $2240 \times 32 \times 30 = 537,600$ *foot-poundals* and this is the amount of work previously done in raising it.

Sources of Energy available to Man.—The chief stores of all terrestrial energy, both kinetic and potential, are—

1. Solar radiation.
2. Wind.
3. Moving water (currents).
4. Head of water.
5. Fuel.
6. Food.
7. Tides.
8. Hot springs and volcanoes.

But the source of energy in at least the first six of these cases may be traced ultimately to the sun. It is the sun's heat, for instance, that causes the inequalities of the temperature and humidity of the atmosphere that produce winds. Ocean currents are caused chiefly by winds and differences of temperature of the water, and therefore they too derive their energy from the solar radiation. It is the sun that gives the water in the mill-pond, the waterfall, and the flowing stream its "head," for it is the sun's heat that raises the water-vapour into the atmosphere, from whence it is deposited as rain or snow on the higher levels of the earth's surface. It is sunshine that enables the chlorophyll or green colouring matter of plants to

decompose the carbon dioxide of the atmosphere, the carbon being assimilated by the plants, and the oxygen set free. And since fuel is formed from the remains of plants we owe its great store of potential energy to the sun. Food is also traceable to the sun, for it is either vegetable or animal, and as higher forms of animal life prey upon lower, even animal food can be traced back to the vegetable world. But naturally we ask, Where does the sun itself derive its enormous radiant energy? The probable explanation will be found on p. 307.

The immense store of energy we possess in the tides (as yet but little used) is due to the energy of motion of the earth and moon, and to the potential energy of the attraction of the moon and sun upon the earth.

The great characteristics of energy are (1) the transformability of energy, (2) the conservation of energy, (3) the degradation of energy.

Transformation of Energy.—Energy is restless. It is continually undergoing transmutation and taking different forms—visible motion, energy of position, sound, light, heat, electricity, magnetism, chemical action, being a few of the almost infinite variety of forms which it assumes. Indeed, Physics has mainly for its subject-matter the study of the forces and phenomena associated with the transformations and redistributions of energy. A few examples of transformation of energy may here be briefly stated :—

1. *The Pendulum.*—When the bob is pulled aside to A (Fig. 6) to start the oscillations work is expended upon it, and the pendulum has a certain amount of energy of position corresponding to this work. Then it moves faster and faster, owing to gravity, till it reaches its lowest point C at the middle of the swing, when the whole of the potential energy has been changed into kinetic. This kinetic energy causes the pendulum to swing to A′, and in this half of the swing gravity makes the pendulum move more and more slowly, for the kinetic energy is being changed into potential, and at A′ the bob possesses only potential energy; and so on. At intermediate positions the energy is partly kinetic and partly potential, and their sum would always be constant were it not that some of the energy is being transformed into heat because of the friction of the air and friction

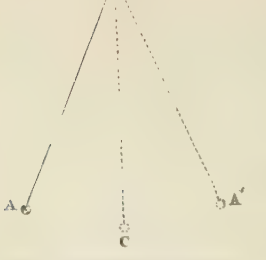


FIG. 6.—Transformation of energy in the pendulum.

at the part where the rod is supported. Were it not for this, the pendulum would continue to swing to and fro through the same arc for ever. But the whole of the original energy is gradually changed into heat, and so the pendulum comes gradually to rest.

2. *A Stone thrown into the Air.*—When it leaves the hand it has kinetic energy. As it ascends it moves more slowly, owing to gravity, and gradually loses this kinetic energy, but it is gaining an equal amount of potential energy or energy of position. At the top of its flight it is at rest for an instant, *i.e.* it has no kinetic energy, only potential. Then, as it descends, the reverse happens; it gradually loses potential and gains kinetic energy. If it had while ascending and descending not heated the air by friction, it would on reaching the level of the hand again have the same amount of kinetic energy as it started with. Then, on striking the ground, all the visible kinetic energy is transformed into heat, for the particles of both the stone and the ground are set in vibration.

Suppose, for example, the stone was thrown with a vertical velocity of 96 feet per second; then, since gravity would, during each second of the ascent, diminish the velocity 32 feet per second, and increase the velocity at the same rate during the fall, therefore the velocity at the end of the successive seconds would be 64, 32, 0, 32, 64, 96 feet per second, and the height at the corresponding times would be found to be 80, 128, 144, 128, 80, 0 feet respectively. Suppose the mass of the stone to be, say, 2 lbs., we may tabulate the results thus:

Time.	Velocity in feet per second.	Height in feet.	Kinetic energy ($\frac{1}{2}MV^2$) in foot-poundals.	Potential energy (MgS) in foot-poundals.
On starting . . .	96	0	9216	0
End of 1st second .	64	80	4096	5120
,, 2nd ,, .	32	128	1024	8192
,, 3rd ,, .	0	144	0	9216
,, 4th ,, .	32	128	1024	8192
,, 5th ,, .	64	80	4096	5120
,, 6th ,, .	96	0	9216	0

Thus, neglecting the friction of the air, we see that at any instant in its journey *the sum of the kinetic and potential energies of the stone is the same as the original kinetic energy*, or—

$$\tfrac{1}{2}MV^2 = \tfrac{1}{2}Mv^2 + Mgh$$

where V is the original velocity, and v the velocity and h the height at any moment.

3. *Sound.*—When a tuning-fork is struck, its arms swing like pendulums, but its vibrations gradually die away as they are communicated to the air and cause the sound heard. The sound ultimately dies away as the vibrations of the air are converted into heat.

4. *In a telephone*, when the diaphragm is caused to vibrate by the speaker, the vibrations are converted into electric currents in the wire. This electric energy is transformed partly into vibrations and sound at the receiver, and partly into heat in the conducting wires.

5. *In an incandescent electric lamp*, the electric current is transformed in the carbon filament into heat and light. Conversely, in an instrument called the *thermopile*, consisting of a large number of junctions of two different metals, heat-energy is transformed into electricity (p. 27).

6. *All chemical changes* are illustrations of transformation of energy. For example, when carbon and oxygen are allowed to unite, as in the burning of coal, the potential energy of chemical attraction is transformed into heat, which may in turn be transformed into mechanical work. Similarly, gunpowder possesses potential energy in virtue of the power of its ingredients, charcoal, sulphur, and saltpetre, to combine with each other and with the constituents of the air. When the combination takes place, this potential energy is transformed into heat, light, and sound, and partly into the kinetic energy imparted to bodies in contact with it—say a bullet in a gun. This kinetic energy in turn is expended partly in heating the air during the flight, and partly in heating the target, and shattering the ball and heating the fragments.

Conservation of Energy.—The above examples show that to obtain energy in any form there must be an expenditure of an exact equivalent in some other form. There can be no creation of energy. Nor can there be destruction of it, for when it disappears in one form it reappears in others. *This principle, that energy cannot be created nor destroyed, and that the total quantity of energy in the universe is constant and cannot be increased nor diminished, is known as the doctrine of the conservation of energy.* It was first published in the early half of the nineteenth century, but it represents the accumulated results of the experiments of generations of scientists. It has been one of the most fruitful conceptions ever introduced into physical science. Before its discovery the various branches of physics, such as dynamics, sound, light, heat, electricity, magnetism, etc., were treated independently of each other, but now we have learned to regard them simply as different ways in which energy and matter may be associated together.

Availability and Degradation of Energy.—It is while energy is undergoing transformation that it does work, and some forms of energy are more capable of undergoing useful transformations than others. Although there is no loss of energy, yet every time a transmutation of energy occurs it passes from a higher or more easily transformable kind to a lower or less easily transformable one. This loss of availability of energy is termed *the degradation or dissipation of energy.* Illustrations of this principle are seen everywhere in nature. Let us study one or two simple cases:—

1. By spending a certain amount of our potential energy in rubbing a button, the button is warmed, the heat produced being exactly equal to the work done. If now the button be allowed to lie for a little time, it is

no longer warm ; it has shared its heat with bodies in contact with it and around it. Heat thus tends continually to diffuse itself so as to equalize temperature, and therefore loses its availability for doing work. When, for example, there is no difference of temperature between the boiler and the condenser of a heat-engine, the engine can do no work, although there may be plenty of heat in it.

2. Coal has potential energy because of the chemical attraction between it and the oxygen of the air. When the coal is burned this becomes converted into heat, and because of the difference of temperature between it and other bodies its energy is available for work, as, for example, in an ordinary steam-engine. But in even the very best engines only about one-fourth of the available energy of the fuel is converted into work, the other three-fourths being dissipated in heating the furnace and engine rooms, in overcoming friction, in heating the water in the condenser, in producing noise, and so on, while a considerable part of the fuel escapes unburnt in the form of soot.

3. The vibrations of a tuning-fork die away because of the friction of the air, and also because of internal friction between the molecules of the fork. The air and the fork are thus both slightly heated.

4. Hold, say, a piece of chalk in front of a mirror, and observe that the image is less distinct than the object itself. This is due to the fact that no mirror is perfect and reflects all the light which falls upon it ; some of the light-energy is absorbed by the mirror and transformed into heat.

Thus we find that at every transformation of energy some of the energy is wasted through conversion into heat, which uniformly diffuses itself among surrounding objects, and therefore can no longer be used by us for producing work. Because of this degradation, the quantity of available energy is continually decreasing. And this is true, not only on the earth, but throughout the whole material universe. Lord Kelvin has shown that at the beginning there must have been a creation of energy, and that since then the total quantity of energy in the universe has remained constant, but that a continual degradation of energy is taking place into the form of heat at one uniform temperature, and therefore quite unavailable for work. When all the energy in the universe has been thus reduced all work must cease, so far as we can at present see, although it is conceivable that this condition of universal stagnation may be avoided by some processes at work, although as yet undiscovered by us.

Simple Pendulum.—A body suspended from a fixed support so that it can swing freely in a vertical plane is a *pendulum*. A *simple pendulum* is one in which the swinging body is concentrated at a point, and is suspended by a perfectly flexible weightless thread. This, of course, is ideal and cannot be realized in practice, for no body consists of a single heavy particle, and no suspending cord or rod is without weight.

The nearest approach to a simple pendulum is a small metal sphere suspended by a very fine thread. All actual pendulums, such as clock pendulums, are *compound*, and the explanation of their motion is very complicated.

In Fig. 6, the movement of the suspended body (called the *bob*) from A to A′ is called a *single vibration* or *oscillation*, and the time taken is called the *time of oscillation*. The length of the arc CA or CA′ is called the *amplitude* of the oscillation. The distance between the point of suspension and the centre of the bob is called the *length* of the pendulum.

Laws of Motion of a Simple Pendulum.—The conditions on which the period of a simple pendulum depends can be deduced from experiment.

To do so, use two small lead balls and one wooden ball all of the same diameter, say about ¾ inch, and a larger lead ball. They should have hooks by means of which they can readily be attached to a fine thread supported as in Fig. 7.

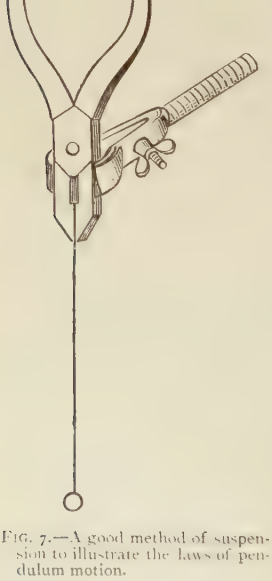


Fig. 7.—A good method of suspension to illustrate the laws of pendulum motion.

Expt. 7.—Suspend, as shown in Fig. 7, one of the smaller lead balls and the larger one each by a thread about 100 cms. long. Adjust the lengths till they swing in exactly the same time. Measure the length of each pendulum, *i.e.* the distance from the lower end of the pliers to the middle of the bob. Are the pendulums alike in every respect except mass? Does the period of a pendulum depend on the mass of its bob?

Expt. 8.—Suspend the wooden ball beside the lead ball of the same diameter, and proceed exactly as in the last experiment. Does the period of a pendulum depend on the kind of material composing its bob?

Expt. 9.—Use the two pendulums adjusted in the last experiment. Pull them aside unequal distances and release them at the same moment. Does the period of a pendulum depend on the amplitude?

Expt. 10.—To find the relation between the period of a pendulum and its length, proceed as follows: Find the length of the pendulum with the utmost care, by first measuring the length of the thread from the pliers to the top of the ball, and then adding to this the radius of the ball (obtained, say, by measuring the diameter of the ball by means of the calipers and scale, and dividing the result by 2). Fix on the upright support of the pendulum a sheet of white paper with a heavy black vertical line, so that

when the pendulum is at rest it hangs exactly in front of the line. Now disturb the pendulum *through a small arc*, and find how many seconds it takes to make, say, 40 oscillations, that is, pass the vertical line 40 times. To get a more accurate result, repeat this three or four times and take the mean. Then divide the mean by 40 to get the time for a single oscillation.

Repeat the experiment with the pendulum much longer, and then much shorter, and record the results of the three cases as follows :—

Trial.	Time (t) in seconds for one oscillation.	t^2	Length (l) in centimetres.	$\frac{l}{t^2}$
1				
2				
3				

What do you infer from the numbers in the last column ? They could not be the same (or very nearly so) unless l and t^2 varied in the same ratio. Hence the square of the period varies as the length of the pendulum, or the period varies as the square root of the length.

The pupils should be required to write a statement as to the conditions on which, according to these experiments, the period of a pendulum depends. Stated concisely, they are—

I. *The time of oscillation does not depend on the mass of the bob, nor on the kind of material of which it is composed.*

II. *The time of oscillation does not depend on the amplitude.*

III. *The time of oscillation is proportional to the square root of the length of the pendulum.* Newton obtained mathematically the following equation :—

$$t = \pi\sqrt{\frac{l}{g}}$$

where t is the time in seconds that the pendulum takes to make a single oscillation from one side to the other, π the ratio of the circumference of a circle to its diameter (viz. $3\frac{1}{7}$, or more exactly 3·1416), l the length of the pendulum in feet, and g the acceleration due to gravity.

This formula embodies all the above laws, for in it there is no mention of the mass of the bob nor of the amplitude of the swing, and therefore the period does not depend on these. But the equation shows that the period varies as the square root of the length of the pendulum. It also gives us a fourth law, namely—

IV. *The time of oscillation is inversely proportional to the square root of the acceleration due to gravity.*

Uses of the Pendulum.

1. *To measure Time.*—So long as the length of a pendulum remains unaltered, and the arc through which it is swinging is not too great, its vibrations take place in equal times, and hence the oscillations of a pendulum afford one of the best practical methods of measuring time. The motion of the pendulum of a clock is kept up by a raised weight or coiled spring, and the number of oscillations is counted by toothed-wheels and indicated by the position of the hands on a graduated dial.

EXPT. 11.—To determine the length of a seconds pendulum—that is, the length of a pendulum that swings from one side to the other in one second—vary the length of a pendulum until it oscillates 60 times in a minute. Measure its length.

It will be found to be about 39·2 inches, but this length varies because the force of gravity varies with latitude. At London its length is 39·139 inches, at Aberdeen 39·195, at Madras 39·027.

If we know the local value of g, then the length of a pendulum oscillating in one second can be calculated from the formula—

$$1 = \pi\sqrt{\frac{l}{g}}$$

2. *To measure g, the Acceleration due to Gravity at a Place.*—By squaring both sides of the equation $t = \pi\sqrt{\frac{l}{g}}$ we get—

$$t^2 = \frac{\pi^2 l}{g}$$

or—

$$g = \frac{\pi^2 l}{t^2}.$$

$\pi^2 = (3{\cdot}1416)^2 = 9{\cdot}87$ nearly, and we therefore get g by finding by experiment the values of l and t, and inserting them in the above equation.

EXPT. 12.—Pull a pendulum, suspended as in Expt. 7, aside about 10°, and set it free, and observe the time taken to make, say, 100 oscillations (a large number is taken to diminish the error arising from the difficulty of allowing for fractions of a second). Divide the time by the number of

oscillations in order to get the period for one. Repeat the experiment with other two lengths, and set down the results thus—

Trial.	l	t	Average l.	Average t.	$g\left(=\frac{9\cdot87l}{t^2}\right)$
1					
2			. . . .	. . . .	. . . .
3					

Suppose, for example, it is found that the average length of the pendulum in the three cases is 56·5 inches, and the average period 1·2 second, then—

$$g = \frac{9\cdot87 \times \frac{56\cdot5}{12} \text{ feet}}{(1\cdot2)^2} = 32\cdot2 \text{ feet per second per second.}$$

The value of g is found by experiments and calculations like the above to be not the same at all parts of the earth. Thus the value of g in feet per second per second at London is 32·19, at Aberdeen 32·2, at Madras 32·09. There are various causes for these differences, but the chief are—(1) the oblateness of the earth, and (2) its rotation. Because of the earth not being perfectly spherical, places on the equator are about 13 miles further from the earth's centre than places at the poles are, and therefore the force of gravity is not so great in equatorial regions. Again, places near the equator describe a larger circle in the 24 hours owing to the earth's rotation than do places in higher latitudes, hence more of the earth's attraction is used up in preventing the body from flying off at a tangent, *i.e.* used up in neutralizing the so-called centrifugal force.

The combined effect of these two causes is to make the value of g vary from 32·09 at the equator to 32·26 at the pole.

3. *To prove the Rotation of the Earth.*—See Foucault's Pendulum (*Elementary Physiography*, p. 264).

4. *To determine the Mean Density of the Earth.*—Sir George Airy found the mean density of the earth by comparing the periods of similar pendulums at the top and bottom of a mine.

Questions.

1. What is meant by unit force? Define (*a*) the foot-pound-second unit of force, (*b*) the centimetre-gram-second unit of force, and (*c*) the British gravitational unit of force.

2. Under what conditions is it correct to say that work has been done?

How are quantities of work measured? Define the F.P.S., the C.G.S., and the British gravitational unit of work.

3. One horse-power being defined as 550 foot-pounds per second, show that it is nearly equivalent to 8·8 cubic feet of water lifted 1 foot high per second. (A cubic foot of water weighs 62½ lbs., nearly.)

4. A man weighing 200 lbs. runs up a stair 30 feet high in 8 seconds. At what rate does he work?

5. A man whose weight is 180 lbs. carries a weight of 40 lbs. up a ladder to a height of 30 feet in 1¼ minute. Find his power—(1) in foot-pounds per minute, (2) in foot-poundals per second, (3) as a fraction of a horse-power.

6. Distinguish between kinetic and potential energy, and state how they are measured.

7. What is the kinetic energy of a locomotive of mass 80 tons moving at the rate of 60 miles an hour—(1) in foot-poundals, (2) in foot-pounds?

8. Explain the terms "conservation of energy," "transmutation of energy," and "degradation of energy," and give good illustrative examples of each.

9. Give notes for a lesson on the dissipation of energy, illustrated by experiment.

10. State the laws of simple pendulum motion, and describe experiments illustrating these laws.

11. What difference would be observed in the rate at which a pendulum would vibrate if taken from London (*a*) towards the poles, (*b*) to the equator? Explain the causes of the difference.

12. Compare the rate of vibration of a pendulum 36 inches long with one 18 inches long. If I took a pendulum of any given length from London to the Equator, what change would be noticed in its rate of vibration?

13. Describe the uses of the pendulum.

14. How can a pendulum be used to measure the acceleration due to gravity?

15. If a pendulum be 13·7 cms. long, and make 807 single oscillations in 5 minutes, what is the value of g at the place?

16. A pendulum 39·2 inches long makes one single oscillation per second. What would be the length of one to vibrate in half a second?

CHAPTER III.

HEAT AND TEMPERATURE.

The Scientific Meaning of the Words "Heat" and "Temperature."—The student should be already familiar with these words in connection with his elementary studies (see *Elementary Physiography*, pp. 50 and 61). He will, therefore, know that the word "heat" is used in science to denote the cause of the sensation of warmth. But what is the *nature* of heat?

EXPT. 13.—Mix in a dish hot and cold water whose temperatures have been previously determined. Compare the temperature of the mixture with that of the hot water and of the cold water.

Since the mixture is colder than the hot water and warmer than the cold water, heat must have been *transferred* from the one to the other.

EXPT. 14.—Take a piece of German silver wire, A (Fig. 8), and of copper wire, B, and twist them firmly at one end, C, with pliers. Join the other ends to a low-resistance galvanometer, G. Warm the junction C of the two metals by a spirit-lamp, and watch the galvanometer.[1] Next immerse C in a mixture of ice and salt, and note the direction of swing of the needle of the galvanometer.

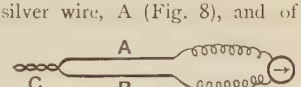


FIG. 8.—To illustrate the transformation of heat into electric energy.

The heat of the flame was *transformed* into electric energy, which deflected the needle of the galvanometer.

[1] Two rods of different metals joined at their extremities are called a *thermo-electric couple*. The strength of current obtained on heating a junction depends on the metals employed. Bismuth and antimony are commonly the metals used. When several thermo-electric couples are joined in series, they form a *thermo-electric pile* or *thermopile*, and in this the current is proportional to the number of alternate junctions heated; hence it is an invaluable instrument for detecting extremely small differences of temperature.

In a later portion of this chapter we shall describe Joule's experiment, by which he proved that heat and mechanical work are mutually convertible, and that a certain amount of work can be transformed into an equivalent amount of heat, there being *no loss nor gain during the transformation.*

But in the last chapter we learned that the characteristics of energy are—

1. That it may be transferred from one body to another.
2. That it may be transformed from one kind into another.
3. That during the transformation there is no loss nor gain.

We have just shown that heat possesses those three characteristics, and therefore we must conclude that *heat is a form of energy.* It is now universally believed that when a body is warm its molecules are vibrating and striking against each other, rebounding and spinning, and also that the atoms composing the molecules are violently agitated; in short, that *heat is the kinetic energy of molecular and atomic vibration.*

Again, if two bodies are placed in contact, one being warm and the other cold, the former imparts molecular energy—that is, heat—to the latter until they are both equally warm. The body that shares its heat with the other is said to have a higher temperature than the other. If there had been no transference of heat, the bodies would have been said to have the same temperature. *Temperature may thus be defined as the condition of a body which determines whether it shall give heat to, or receive heat from, others with which it is in contact. If heat passes from a body A to a body B, then A is said to have a higher temperature than B; and if no heat passes either from A to B or from B to A, then A and B are said to have the same temperature.*

The instrument used for accurately comparing the temperatures of bodies is called the thermometer, and we take for granted that his study of the elementary stage of this science has familiarized the reader with the construction and action of the ordinary mercurial thermometer.

Registering Thermometers.—A registering thermometer is one used for indicating the highest and the lowest temperature since the instrument was last adjusted.

1. *The photographic self-registering thermometer, or thermograph*, records not merely the highest and lowest temperature, but also all the variations of temperature during the period. The following is the principle of the instrument: Photographic

paper is mounted on a vertical cylinder (Fig. 9), which is slowly turned round by clockwork once in 24 hours. Immediately in front of the cylinder is a screen with a narrow vertical slit in

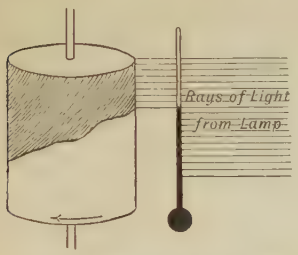


FIG. 9.—Principle of the photographic registering thermometer.

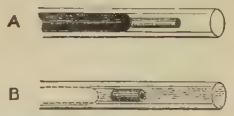


FIG. 10.—A, showing index outside mercury (represented black) in maximum thermometer. Surface of mercury resists being broken, and therefore index pushed forward by expansion of mercury. B, showing index inside alcohol (represented shaded) in minimum thermometer, and therefore pulled back by the surface of the alcohol when the alcohol contracts.

which is placed a thermometer. A beam of parallel rays from a distant lamp strikes the vertical slit. Since mercury is opaque, only the part of the paper above the top of the mercury is discoloured by the light. As the mercury rises and falls, and the paper is carried steadily past, there is a wavy curve formed between the blackened part of the paper above and the unaffected part below, and thus the mercury leaves upon the paper a record of its height at each instant during the 24 hours.

2. *Ordinary maximum and minimum thermometers* are registering ones.

(*a*) *Rutherford's Maximum and Minimum Thermometer.*—The student should read again carefully the description of this instrument in *Elementary Physiography*, p. 57. Fig. 10 may help the reader to more clearly understand the motion of the index in the maximum and the minimum thermometer respectively.

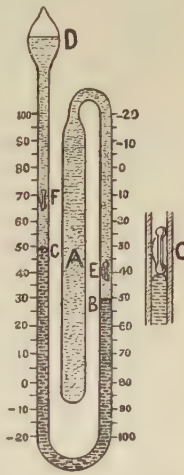


FIG. 11.—Six's maximum and minimum thermometer. (From Watson's *Text-Book of Physics*.)

(*b*) *Six's maximum and minimum thermometer* shows both the maximum and minimum temperature by one instrument. It consists of a fine glass tube bent as shown in Fig. 11. The large bulb A is filled with alcohol, which is the thermometric liquid used. The small bulb D is

partially filled with the same liquid. The two portions of alcohol are separated from each other by a thread of mercury (represented by the darker shading from B to C). In the alcohol are two glass indexes, E and F, which are slightly pressed against the side of the tube by a fine steel hair-spring, as shown at G, and are thus prevented from slipping down the tube by their own weight. At the beginning of an observation the indexes are in contact with the mercury. Suppose a rise of temperature afterwards takes place, the alcohol in A will expand and push the mercury round from right to left, which in turn will push up the index F. Thus *the lower end of* F *marks the maximum temperature.* If a fall of temperature takes place, the alcohol in A will contract, and the mercury will follow up the receding alcohol and push before it the index E, *the lower end of which therefore marks the minimum temperature.*

The alcohol in D does not affect the readings, for it has room to expand without pushing the mercury; and when the alcohol in D contracts, its surface merely sinks a little.

For special purposes, such as finding the temperature at great depths in the earth's crust or in the ocean, special forms of registering thermometers are used.

3. *Maximum Thermometers for recording Underground Temperatures.*

(*a*) *The Slow-action Thermometer.*—In it means are taken to prevent the thermometer being quickly affected by changes of temperature, so that there is time to hastily draw it up to the surface before the reading alters. To secure this the bulb is embedded in some non-conductor of heat such as stearine or felt (A, Fig. 12).

(*b*) *Negretti and Zambra's Inverted Maximum Thermometer* consists of an inverted thermometer with a constriction and bend in the bore near the bulb. Before an observation is made with it, it is held with the bulb downwards, so that the mercury occupies the bulb and lower part of the stem. In this position it is placed in water at a lower temperature than that expected during the subsequent observation, in order to make sure that there is sufficient mercury in the bulb and the stem up to the constriction. The instrument is then carefully inverted so that the bulb is now upwards as in B, Fig. 12, and the mercury below the constriction falls to the bottom of the stem. In this position the instrument is lowered to the place the temperature of which is required. The mercury in the bulb expands with a rise of temperature, and part is forced past

the constriction. After a time the instrument is taken up to be read, and this causes the temperature to fall and the mercury to contract; but the part of it that has been forced below the constriction cannot get back again, and breaks off and falls to the bottom of the stem, which is there graduated. The graduation corresponds with that of a standard instrument, and hence, from the level of the upper surface of the mercury in the lower part of the stem, we know the highest temperature during the observation. The instrument is then held with the bulb downwards, and gently tapped until all the mercury is reunited in the bulb and lower part of the stem, and the thermometer is then ready for another observation.

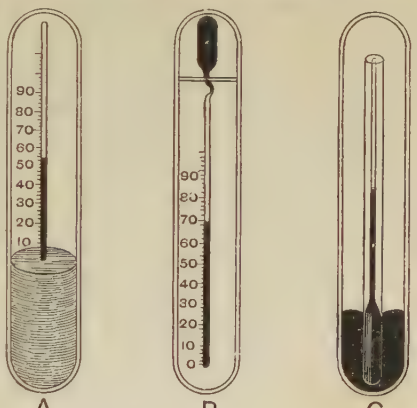


FIG. 12.—Registering thermometers used for determining the temperature of the earth's crust. A, Slow-action thermometer; B, Negretti and Zambra's inverted thermometer; C, Magnus's overflow thermometer.

(*c*) *Magnus's Overflow Thermometer* is the one used in Germany for measuring underground temperature, and one on the same principle is used in France. The stem containing the mercury is open at the top, and is placed inside a hermetically sealed glass tube from which the air has been exhausted (C, Fig. 12). As the temperature rises the mercury in the bulb and stem expands and overflows into the intermediate space. We can tell what was the highest temperature reached thus: Place the Magnus thermometer and also an ordinary one in a vessel containing cold water, and gradually heat the water and observe at what temperature on the ordinary thermometer the mercury in the stem of the Magnus thermometer is just up to the level of the orifice. This is the highest point the mercury left in the stem reached before, and hence the reading on the ordinary thermometer at that moment gives the maximum temperature to which the Magnus instrument was previously subjected.

4. *Deep-sea Registering Thermometers.*—Six's maximum and

minimum thermometer and Negretti's inverted thermometer have been employed for ascertaining the temperature at the bottom and intermediate depths of the ocean, but when used for this purpose they have to be protected from the enormous pressure of the water (about one ton per square inch for every 1000 fathoms below the surface), which would either crush them altogether, or, at any rate, cause the readings to be too high because of the compression of the bulb. Hence the bulb is surrounded by an outer covering of very strong glass, and the space between the bulbs and this protecting sheath is about three-fourths filled with alcohol, in order that the heat may readily be conducted from the water to the thermometer. We said that the space between the bulb and the outer glass is only partially filled with the conducting liquid, the rest of the space containing vapour of the liquid; hence when the outer glass is compressed, it in turn compresses the vapour, thus relieving entirely the enclosed thermometer bulb from pressure (see also p. 177).

Pyrometers (Gr., *pyr*, fire; *metron*, a measure) are instruments for measuring higher temperatures than a mercurial thermometer could register. There are many different forms of them, making use of nearly every effect produced by change of temperature. We have only space to describe the principle of two classes of electrical pyrometers.

1. *Pyrometers depending on the Variation of the Electrical Resistance of a Wire with Change of Temperature.*—The resistance that a wire offers to the passage of an electric current increases with rise of temperature, but for a definite temperature the resistance is always the same. Sir William Siemens utilized this principle. He coiled a very fine platinum wire round a porcelain cylinder, and inserted the cylinder into an iron tube, which was then placed in the furnace or other region whose temperature it was required to ascertain. The ends of the wire were connected with a galvanometer and an instrument known as a resistance box. By means of these the resistance of the wire was measured, and this being known, the temperature was at once found by means of a formula previously obtained by experiment, and giving the relation between resistance and temperature.

In an improved form of this instrument devised by Mr. Callendar the platinum wire is wound on a mica plate, and with the aid of a sensitive galvanometer it is said to furnish results accurate to 0·1° C. for temperatures over 1000° C.

2. *Thermo-electric Pyrometers.*—If two dissimilar metals be joined together at both ends, and one of the junctions be heated, an electric current is produced whose strength is proportional to the difference of temperature of the two junctions, and also depends on the metals employed (see Expt. 14, p. 27). The law connecting the strength of the current with the difference of temperature of the junctions can be ascertained by experiments in which known differences of temperature are employed; and when this has been obtained, we can in turn use it to measure temperatures by the strength of current produced. The two metals platinum and palladium can be raised to a very high temperature without melting, and are therefore frequently the two metals used in the instrument. One junction is placed in the region whose temperature we wish to measure, and the other junction is placed in a bath. From the strength of current produced we can tell the difference of temperature of the two junctions; but the temperature of the bath is known, therefore that of the other junction can be calculated. The platinum-palladium couple gives fairly accurate results up to 1500° C.

Electrical pyrometers have been used to measure not only high temperatures but very low ones, and also to measure temperatures in inaccessible places, such as the bottom of the sea.

Unit of Heat.—Since heat is a form of energy, it is a measurable quantity, and it is therefore necessary to have a unit in terms of which to express the quantity of heat which is being measured. It is convenient to base the unit on one of the commonest effects of heat, namely, change of temperature, and *the unit of heat is the quantity of heat required to raise the temperature of unit mass of pure water* 1° *C.* This definition leaves the unit of mass open:—

1. In the C.G.S. system the unit of mass is a gram, and the corresponding unit of heat is called the CALORIE, which is therefore *the quantity of heat required to raise the temperature of* 1 *gram of water* 1° *C.*

2. In the British system the unit of mass is a pound, and corresponding to it we have the POUND DEGREE UNIT OF HEAT, which is therefore *the quantity of heat required to raise the temperature of* 1 *lb. of water* 1° *C.* Since a pound is equal to 453·59 grams, this unit is equal to 453·59 calories.

Of course if these units were expressed in the Fahrenheit scale they would be $\frac{5}{9}$ of the above values.

Experiments show that the amount of heat required to raise the

temperature of water 1° C. depends upon the temperature at which we start, and that it diminishes by about 1 per cent. between 0° and 29° C., where its value is a minimum, and then increases up to the boiling-point. For ordinary purposes this variation is negligible, but for accurate work it is necessary to say at what temperature the calorie is taken. There are strong theoretical reasons for taking it at 10° C., which is, moreover, not far from the average temperature of temperate climates. The calorie would then be defined as the quantity of heat required to raise the temperature of 1 gram of pure water from 10° C. to 11° C.

Specific Heat.

EXPT. 15.—Take a few balls of equal mass but of different metals, say iron, tin, lead, and bismuth, and suspend them for a short time in oil heated to about 150° C.; then place them on the surface of a thick cake of beeswax, and observe which melts most wax.

Each of the balls was, at the commencement, at the same temperature as the oil, and when they just ceased to sink they must have been again at the same temperature—the melting-point of the wax. But the one that melted most wax must

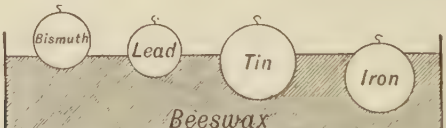


FIG. 13.—Experiment to show that different metals have different specific heats.

have given up most heat in cooling from the one temperature to the other, and, conversely, it must have absorbed most heat from the oil—that is to say, it had the greatest *capacity for heat*, for it took most heat to raise it to the same temperature as the others.

In order to compare the capacities of different bodies for heat, we compare each with water, which has the greatest capacity for heat of all known solids and liquids, and the ratio of the capacity of any substance for heat to the capacity of water for heat is called the SPECIFIC HEAT of the substance. Hence *the specific heat of a substance is the ratio of the number of units of heat required to raise the temperature of any mass of that substance* 1° *C., to the number of units of heat required to raise the temperature of an equal mass of water* 1° *C.*; or, more briefly, *the specific heat of a substance is the number of units of heat required to raise the temperature of unit mass* (1 *gm.*) *of*

it 1° *C.* But we have already defined the unit of heat as the amount of heat required to raise the temperature of unit mass of water 1° C., hence the specific heat of water is 1. The specific heat of ice is 0·5, and of steam 0·48. The differences between the specific heats of different substances arise from the fact that they require different quantities of heat to overcome their molecular attractions, and set their molecules in the state of vibration we call heat.

The term *thermal capacity* is used for the quantity of heat required to raise the temperature of a body 1°. If H units of heat raise the temperature of a body from t to t',

$$\text{its thermal capacity} = \frac{H}{t' - t}.$$

If m be the mass of the body, then it is evident, from the second definition of specific heat given above, that—

$$\text{specific heat} = \frac{H}{m(t' - t)}.$$

Measurement of the Specific Heat of a Substance by the Method of Mixtures.—There are many different methods of measuring specific heat. We shall describe the commonest—that known as the method of mixtures—and for other methods books on Heat should be consulted. The principle involved in the method of mixtures consists in mixing or placing in intimate contact two bodies at different temperatures, so that heat flows from the hot one to the cold till they are both at the same temperature. Then—

HEAT LOST BY THE HOT BODY = HEAT GAINED BY THE COLD BODY.

But if S denote the specific heat, then by the second equation in the last paragraph—

$$\frac{H}{m(t' - t)} = S$$

or—

$$H = Sm(t' - t)$$

that is to say—

THE QUANTITY OF HEAT INVOLVED IN ANY CHANGE OF TEMPERATURE = SPECIFIC HEAT × MASS × CHANGE OF TEMPERATURE.

But we have stated that the heat lost by the hot body is equal to the heat gained by the cold one; therefore—

$$\left.\begin{array}{l}\text{SPECIFIC HEAT OF WARM}\\ \text{BODY} \times \text{ITS MASS} \times \text{ITS}\\ \text{FALL OF TEMPERATURE}\end{array}\right\} = \left\{\begin{array}{l}\text{SPECIFIC HEAT OF COLD BODY}\\ \times \text{ITS MASS} \times \text{ITS RISE OF}\\ \text{TEMPERATURE.}\end{array}\right.$$

The cold substance used is generally water, the specific heat of which is 1. A known mass of cold water at a known temperature is put into an apparatus called a *calorimeter*. A simple one is represented in Fig. 14. It consists of a cylindrical thin copper vessel, about 12 cms. high and 8 cms. in diameter. It is supported on corks (which are shaded in the diagram), and placed inside a wooden box. In the wooden lid are two openings, in one of which is fixed a thermometer, T, and through the other passes a stirrer, S, for stirring water placed in the vessel (the thermometer may be used as a stirrer). A warm body placed in this vessel suffers very little loss of heat, because the copper, being thin, takes very little heat from the body, and also because the vessel is surrounded by bad conductors—air, wood, and cork.

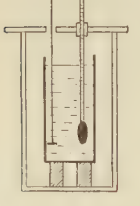


FIG. 14.—A calorimeter.

Fig. 15 represents a simple apparatus recommended by Messrs. Schuster and Lees (*Intermediate Course of Practical Physics*) for heating the body whose specific heat we wish to determine. The substance to be heated is placed in a test-tube, A, along with a thermometer, T. If the substance is a bad-conducting solid, it should be reduced to small fragments before being placed in A. The test-tube passes through the tight-fitting cork, C, of a beaker or tin canister, D, which is about one-third full of water. The water and test-tube are then heated, and the steam escapes through the tube B. After the water has been boiling for some time, the substance is poured into the calorimeter, as shown in Fig. 16. The water in the calorimeter is then stirred until it and the substance placed in it are at the same temperature, which is then noted; and, having previously weighed the substance and weighed the water, we have now all the data required for telling the specific heat of the substance.

Example.—Twenty-four gms. of iron filings at 100° C. are immersed in

10 gms. of water at 15° C., and the mixture acquires a temperature of 33° C. What is the specific heat of iron?

$$\left.\begin{matrix}\text{Specific heat of iron} \times \text{mass} \\ \times \text{ fall of temperature}\end{matrix}\right\} = \left\{\begin{matrix}\text{specific heat of water} \times \text{mass} \\ \times \text{ rise of temperature}\end{matrix}\right.$$

that is—

$$\text{Specific heat of iron} \times 24 \times 67 = 1 \times 10 \times 18$$

whence specific heat of iron $= 0{\cdot}112$ nearly.

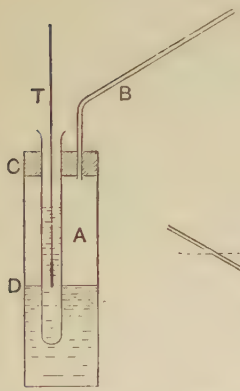


FIG. 15.—Apparatus for heating substances in specific heat experiments.

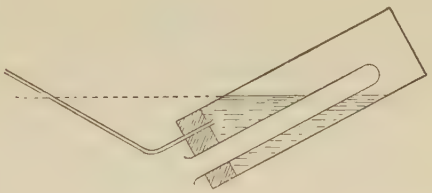


FIG. 16.—Method of pouring the heated substance into the calorimeter so that no water escapes along with it.

If the substance is a liquid (for example, mercury) which does not chemically combine with water, the method of procedure is exactly as above.

In order to secure accurate results in these calorimetric experiments, a number of precautions have to be taken. (1) The amount of heat absorbed from the hot body by the metal of the calorimeter, and by the thermometer and stirrer in it, has to be taken into account. (2) The amount of heat lost should be as small as possible (*a*) during the transference of the substance from the heater into the calorimeter, (*b*) by conduction, convection, and radiation from the calorimeter. But we must refer the student to text-books on Heat for the methods of coping with these difficulties.

EXAMPLES OF SPECIFIC HEATS.

Water	1·000	Mercury	0·033
Ice	0·504	Lead	0·031
Air	0·237	Copper	0·095
Oxygen	0·218	Brass	0·086
Hydrogen	3·409	Iron	0·114

Latent Heat.—When heat enters a body it may produce a change of state without any rise of temperature. The heat absorbed in this way is called latent heat; it is transformed into potential energy amongst the molecules separated, and if we reverse the process, and bring the body into its original molecular state, it gives out exactly the same amount of heat as was absorbed, the potential energy being once more transformed into kinetic.

It is found by experiment that it takes 80 units of heat to melt a unit mass of ice at 0° C. without raising its temperature. This is expressed by saying that *the latent heat of fusion of ice*, or, more briefly, *the latent heat of water*, is 80. Similarly, it is found that 537 units of heat are required to change a unit mass of water at boiling-point into steam at the same temperature. Hence we may define *the latent heat of fusion of a substance* (*also called the latent heat of the liquid*) *as the number of units of heat required to convert unit mass* (1 *gm.*) *of it from the solid to the liquid state without changing the temperature.*

The latent heat of vaporisation of a substance (*also called the latent heat of the vapour*) *is the number of units of heat required to convert unit mass of the liquid into the gaseous state without changing the temperature.*

If L be the latent heat of a substance, and H the total quantity of heat required to make a mass m of it change its state, then, according to definition, each unit of mass absorbs L units of heat, therefore the m units of mass will absorb mL units of heat; that is—

$$H = mL$$

that is—

QUANTITY OF HEAT ABSORBED DURING A CHANGE OF STATE = MASS × LATENT HEAT.

If the body were re-converted into its original state the same quantity of heat would be given out.

Determination of the Latent Heat of Fusion of Ice.—This may be effected experimentally by the method of mixtures.

EXPT. 16.—Weigh the calorimeter, then nearly fill it with water a little above the temperature of the room (with water at, say, 18° C.), and weigh again to find the weight of water. Suppose this is found to be 64 gms. Take a number of fragments of ice, dry them well with blotting-paper, and place them in the water in the calorimeter. Keep stirring the water, and take readings of the thermometer in it till the temperature ceases to

fall and begins to rise; then all the ice is melted. Suppose the reading to be 10° C., and that the mass of ice melted is found by re-weighing the calorimeter to be 5·7 gms. What is, according to your experiment, the latent heat of ice?

The heat given up by the water has done two things—it has first of all melted the ice, and then it has raised the temperature of the water so formed from freezing-point to the common temperature of the mixture. Hence—

Heat given up by water in calorimeter = heat absorbed in changing ice to water + heat required to raise this water from 0° to 10° C.

that is—

Sp. heat of water × mass × fall of temperature = Mass of ice × latent heat + Sp. heat of water × mass of water formed × rise of temperature

that is,

$$1 \times 64 \times 8 = 5{\cdot}7 \times L + 1 \times 5{\cdot}7 \times 10$$
$$\therefore 5{\cdot}7L = 512 - 57$$
$$\therefore L = 80 \text{ nearly.}$$

The above is merely the principle of the method without the refinements necessary. We have not, for example, allowed for the heat given up by the metal of the calorimeter to the ice, nor have we mentioned the precautions taken to prevent loss of heat during the experiment.

The latent heat of fusion of other solids may be obtained in a similar manner by placing them in a liquid at a high enough temperature to melt them.

The Mechanical Equivalent of Heat.—Heat being a form of energy, we can change mechanical energy into heat energy, and, conversely, we can change heat into mechanical energy; and from the law of conservation of energy it follows that from a given quantity of mechanical energy we can by transformation obtain a definite quantity of heat, and *vice versâ* when heat is transformed into mechanical energy. But we express mechanical energy in foot-pounds, ergs, etc., while we measure heat in calories. There must, therefore, be a definite numerical relation between the two sets of units. A calorie must be equivalent to a certain number of foot-pounds or ergs, and this number is called the mechanical equivalent of

heat. Therefore *the mechanical equivalent of heat is the number of units of work (mechanical energy) which is equal to one unit of heat.*

Experimental Determination of the Mechanical Equivalent of Heat.—Dr. Joule, of Manchester, was the first to find experimentally this numerical relation between the number of units of work expended and the number of units of heat produced. The following is an outline of his method. He used a polished copper calorimeter, C (Fig. 17), containing water. Passing down into the calorimeter there was a brass spindle, S, carrying brass paddles (represented black). Lead weights, W, were suspended by string passing round the axles,

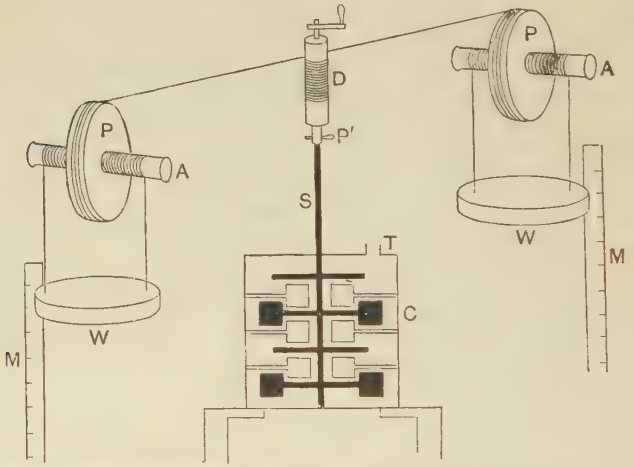


FIG. 17.—Diagram of Joule's apparatus for determining the mechanical equivalent of heat.

A, so that when the weights descended (which they did simultaneously), they caused the drum, D, to rotate by means of strings coiled round the pulleys, P. In this way, when the weights fell the spindle and paddles were made to rotate rapidly, and the water was violently stirred. To prevent the water from merely swirling round, there were projections from the side of the calorimeter that fitted in between the paddles as a key fits the wards of a lock. The temperature of the water was found by a thermometer inserted through the opening T at the beginning, and again at the end after the water had been

heated by the friction. The distance that the weights fell (in Joule's experiment about 63 feet) was measured by scales M. After they had descended, a pin, P', was taken out so that the weights could be raised again without moving the paddles. Then the weights were allowed to fall once more, and this operation was repeated about twenty times. Then the work expended was known, being the product of each weight into the total distance through which it fell. Also the number of units of heat produced was known, being the product of the mass of the water into its rise of temperature. And thus he found that to produce heat sufficient to raise the temperature of 1 lb. of water 1° F. required the expenditure of 772 foot-pounds of work. 772 *foot-pounds of work are therefore called the mechanical equivalent of heat, for this amount of work can produce one unit of heat.* Since 1° C. = $\frac{9}{5}$° F., therefore the mechanical equivalent of heat in the Centigrade scale is $772 \times \frac{9}{5}$, or 1390 foot-pounds.

Joule performed his experiments about 1850. Professor Rowland, of Baltimore, in 1879 employed a similar method but with greatly improved apparatus, and probably his is the most complete study of the subject that has ever been made. The paddles were more elaborate in design, and were turned by a steam-engine, thus securing a much more rapid rise of temperature. The mercurial thermometer produced errors of 1 or 2 per cent., and therefore Rowland used an air-thermometer instead. He found that Joule's values were too low, and that the mechanical equivalent of heat is 777 foot-pounds using the Fahrenheit scale, or 1404 foot-pounds in the Centigrade scale.

Questions.

1. What is a maximum and minimum thermometer, and for what purposes is it used? Describe any form of the instrument with which you are acquainted.
2. Describe one form of maximum thermometer and one form of minimum thermometer.
3. Why is it necessary to support an ordinary minimum or maximum thermometer in a horizontal position?
4. Describe a thermometer used (*a*) for finding underground temperatures, (*b*) for finding deep-sea temperatures.
5. In what way has the temperature of the deep-seated rocks of the earth's crust been determined?
6. For what purposes are pyrometers intended? Describe some form of electrical pyrometer.
7. What does one mean by a body's "capacity for heat"? Explain fully the statement that the capacity of quicksilver for heat is one-thirtieth that of water.
8. What is meant by the specific heat of a substance? How would you find the specific heat of a florin?
9. 1 lb. of water and 1 lb. of lead are heated to the same temperature,

and each is then mixed with 1 lb. of water at the temperature of the room. Which will produce the greatest heating effect, and why?

10. Describe an experiment by which you could illustrate the difference in specific heat between water and mercury.

11. Explain the meaning of latent heat, and define the term quantitatively.

12. Two vessels, one containing pounded ice and the other water at a temperature of 32° F., have thermometers placed in them, and are then heated from the same source. State what difference will be noticed in the records of the two thermometers and the cause of the difference.

13. State what is meant by the mechanical equivalent of heat, and explain a method by which it has been determined.

14. How much heat would be required to raise the temperature of 1 kilogram of lead 10° C.? How much heat would be required to raise the temperature of 1 kilogram of water 10° C.?

15. The mass of a copper calorimeter was 30·32 gms., and it contained 250 gms. of water at 15° C. Afterwards 150 gms. of water at 98° C. were added. What was the final temperature (specific heat of copper 0·095)?

16. 5 gms. of iron give out 44·96 calories on cooling from 80° C. to 0° C. Find its specific heat. From the answer, find how many calories will be required to warm 25 gms. from 10° C. to 40° C.

17. 12 gms. of iron filings at 100° C. are immersed in 5 gms. of water at 15° C., and the mixture acquires a temperature of 33° C. Find the specific heat of iron.

CHAPTER IV.

WAVE-MOTION IN WATER, AIR, AND ETHER.

Wave-motion.—If a pebble be dropped upon the smooth surface of water in a pond, the particles of water under the stone are depressed, and those around are therefore ridged up, forming a circular crest. But the particles thus elevated are pulled down again by gravity, so that a circular trough is formed, and the particles beyond are thereby forced up and form a crest. These in turn fall and force up the particles beyond them, and so on. And thus the disturbance spreads outwards in all directions from the place where the stone entered the water, and a succession of moving crests and troughs follow each other in concentric circles across the pool. The particles of water do not move forward with the wave, for pieces of cork or wood floating on the surface of the water simply rise and fall. Each particle of water merely moves up and down a little. Thus if A in Fig. 18 represents the position of a particle when undisturbed, then when a succession of waves is passing, it moves from A to A_1, thence to A_2, then back to A_1, and so on.

There is another class of waves roughly exemplified by those seen travelling over a cornfield, from one side to the other, before the wind. If the upper row of dots in Fig. 20 be taken to represent the ears of corn at rest, the spaces between them being regarded as equal, then as the waves travel over the field the ears are crowded together in some places and spaced out in others, as represented in the third row of Fig. 20. The motion of any one ear is from B (Fig. 18) forward to B_1, and thence back to B_2, and so on.

FIG. 18.—Preliminary notion of the motion of particles in transverse and longitudinal waves.

We thus see that there are two types of waves, viz. *transverse*

waves, in which the motion of the particles is at right angles to the direction in which the waves are travelling, and *longitudinal waves*, in which the particles move to and fro along the direction in which the waves are passing.

Expt. 17.—Take a piece of rubber tubing or soft rope two or three metres long. Hold one end in the hand while the other parts are lying straight on a table or the floor, and move the hand rapidly backwards and forwards (Fig. 19). A series of transverse waves is set up proceeding from

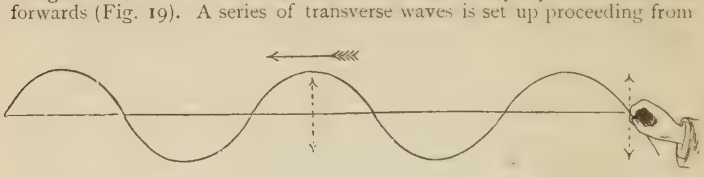


Fig. 19.—Transverse waves produced in a piece of rubber tubing or soft rope.

the hand to the other end, each part of the rope executing in succession a transverse motion like that of the hand.

Expt. 18.—Fasten one end of the indiarubber tubing to a peg at a suitable height in the wall. Make a distinct chalk mark near the top of the tube ; hold the lower end so that the tube is slightly stretched, and with the fingers of the other hand rub the tubing in the direction of its length. A longitudinal wave passes along the tubing, as is shown by the up-and-down movement of the mark.

Expt. 19.—Wrap a brass or copper wire round a thick piece of glass tubing, so that the coils touch each other. On removing the wire it forms a spiral. Support horizontally two parallel wooden rods about 18 inches apart, and suspend the spiral from them by, say, every tenth coil being supported by two threads, one of which is attached to each rod, so that the spiral is horizontal and parallel to the rods and about 18 inches below them. The following dimensions will be found suitable: about 15 metres of wire, No. 15 gauge, coiled closely round a tube 7 cms. in diameter, and then adjusted to a length of 2 metres, and suspended by threads 60 cms. long.

Gather together a few coils at one end into the hand, and on suddenly releasing them observe the compression travelling to the other end of the spiral. The to-and-fro motion of the parts can be more easily seen by gumming little strips of paper to the lower part of a few of the coils.

Definitions of Certain Terms applied to Wave-motion.—From the above examples we see that *a wave may be defined as a form or disturbance handed on from one portion of a medium to another, owing to the successive periodic vibrations of the particles of the medium about their mean positions.*

Hence the chief characteristics of wave-motion are—

1. That a certain form or state of motion travels along the medium, but the particles of the medium themselves do not travel onwards, but vibrate about their position of rest. It is energy, not matter, that is transmitted.

2. That in uniform media waves proceed in straight lines from their starting-point outwards in all possible directions. But in some cases the particles of the medium vibrate at right angles to the direction of the wave, and in other cases in the same direction as the wave. When the direction of vibration is perpendicular to the direction of propagation, the wave is called a *transverse wave;* when the direction of vibration is parallel to that of propagation, the wave is called a *longitudinal wave.* Waves in water and radiation-waves in ether are transverse, while sound-waves in air and earthquake-waves in the earth's crust are longitudinal ones. In Fig. 20 the movement of the particles in the two types of waves is represented diagrammatically.

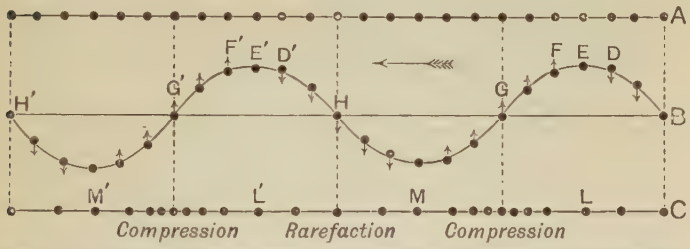


FIG. 20.—Comparison of the movement of the particles in transverse and longitudinal waves. A, a row of particles undisturbed; B, arrangement of the particles in transverse waves; C, arrangement of the particles in longitudinal waves.

It will be seen from the figure that transverse waves consist of alternate crests and troughs, and longitudinal waves of alternate compressions and rarefactions, and that a compression corresponds to the downward slope from a crest to the next trough, and a rarefaction to the upward slope from the trough to the next crest. The particles represented in the transverse waves were originally distributed along the horizontal line B, but now their simultaneous positions and directions of motion (as shown by the small arrows) are different. The particle E is in its highest position at the crest of the wave. A short time earlier D was in that position, but is now moving downwards towards its original position in the line B; and a little later F, which is now moving upwards, will be at the crest, and E will be moving down just like D. In this manner the wave passes on from right to left, as indicated by the large arrow.

Any two particles in a wave which are in similar positions in their path, and moving in the same direction, are said to be in the

same phase. Thus, in Fig. 20, D and D′ are in the same phase, so are F and F′, L and L′, etc.; but D and F are in opposite phases, so are G and H, L and M, etc.

A wave-length is the distance, measured in a straight line in the direction of the wave, from any particle to the next particle in the same phase. Thus DD′, EE′, GG′, LL′, MM′, etc., are wave-lengths, and GH, LM, etc., are half wave-lengths. A wave-length, therefore, in a transverse wave is the distance between successive crests or successive troughs, and in a longitudinal wave it is the distance between the centres of two successive compressions or of two successive rarefactions. How many wave-lengths are shown in the diagram?

The *amplitude* is the extent of swing of each particle on either side of its position of rest.

The *period*, or *periodic time*, is the time taken by each particle to completely describe its path.

The *wave-frequency* is the number of waves that pass a given point in a second. Of course the wave-frequency is inversely proportional to the wave-length, for the greater the length of the waves the fewer pass a point in a second, and *vice versâ*.

Wave-length determines the pitch of a note in the case of sound, and colour in the case of light; the longer the wave-length in air the lower the pitch, and similarly the longest rays of light in ether give rise to the sensation of red colour, and the shortest ones of violet.

Again, it is the amplitude that determines the intensity of a sound or of light. The amplitude and intensity diminish with increased distance from the source, the intensity being always inversely as the square of the distance from the starting-point.

Water-waves.—We have said that the particles of water in a wave rise and fall in straight lines. A close examination will show that this is not exactly the case. The motion can best be studied by using a long narrow rectangular trough (say 4 feet by 6 inches by 6 inches), preferably with one of the long faces made of glass.

Expt. 20.—Nearly fill such a trough with water, and by mixing beeswax with iron filings make little pellets that will float at various depths. Start waves by lowering and then raising at one end of the trough a flat piece of wood almost as wide as the trough. Observe the motion of the pellets.

Only the form of the wave goes on, and each particle describes a small ellipse (as shown in A, Fig. 21) in a vertical plane lying

along the direction in which the wave travels, and with its major axis horizontal. This is the case with shallow water-waves, but in deep water the path of each particle is a vertical circle whose diameter is the perpendicular distance between

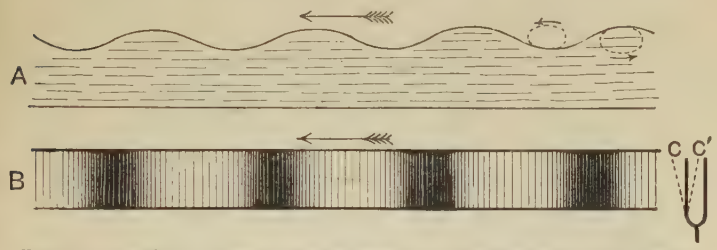


FIG. 21.—A, section of a wave in shallow water. The particles move in little vertical ellipses. In deep water they move in vertical circles. B, section of a longitudinal wave. The darker shading represents compressions and the lighter parts rarefactions.

the crest and trough. In every case a particle goes once round in its path in the time that the wave travels forward a distance of a wave-length.

It should be noticed that the fall and rise of the water in a wave are due to gravity, and hence waves in water are called gravitational waves. But, as Lord Kelvin has pointed out, gravity is not the only cause tending to bring the surface back to its undisturbed condition. A secondary cause is the surface tension, which acts as if there were a thin elastic membrane stretched over the surface, and tending to flatten down the elevated portions and level up the depressed ones.

Origin of Sound.

EXPT. 21.—Let a stretched cord be plucked at its middle point; it will emit a sound, and will be seen to vibrate. Strike a bell or a tuning-fork; a sound is heard, but no vibrations may be seen. Suspend, however, a pith-ball so as to touch the sounding-bell or tuning-fork, and observe its movements. Sound an organ-pipe, and lower into it a horizontal paper tambourine bearing a little sand, and observe the violent agitation of the sand.

In all these cases the difference between the body sounding and silent consists in its vibrations; hence the origin of sound is the vibration of elastic bodies.

A Material Medium is necessary for the Transmission of Sound.—The next question is, How is the sound carried from the vibrating body to the ear?

Expt. 22.—Set the alarum of a clock so that it will sound in a few minutes, and place the clock on some cotton-wool under the receiver of an air-pump (Fig. 22). Gradually exhaust the receiver, and note the effect on the sound of the bell. Re-admit the air, and observe the effect.

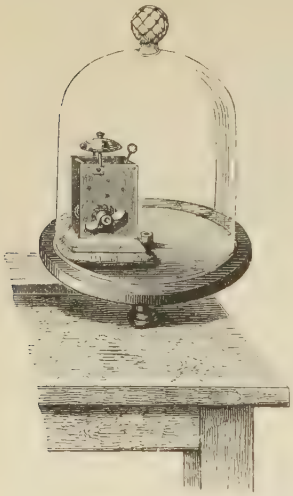


Fig. 22.—A vacuum cannot transmit sound.

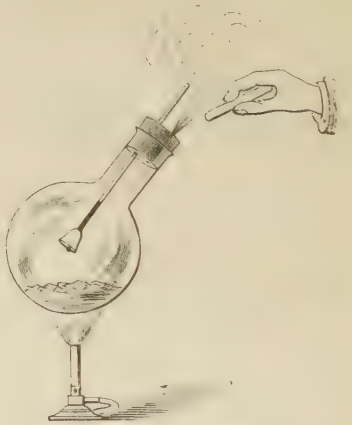


Fig. 23.—A vacuum cannot transmit sound. (From Wright's *Sound, Light, and Heat.*)

The sound, at first distinct, grows fainter and fainter, and at last practically ceases; and as the air re-enters the receiver, the sound of the bell becomes as distinct as at first.

Expt. 23.—The foregoing experiment can be performed without an air-pump. Take a *strong* glass flask (Fig. 23), having a tight-fitting rubber cork with two holes through it. Pass a glass rod through one hole, and to the lower end of it attach a short piece of rubber tubing carrying a toy bell. Put a little water into the flask, and carefully heat it until it boils violently; then remove the flame, and at the same moment close the other hole with a glass rod. As the flask cools, the steam will condense and leave a pretty good vacuum. Shake the flask, and compare the loudness of the sound with that heard before the air was driven out.

Hence some elastic medium is necessary between the vibrating body and the ear for the transmission of sound. Air is usually the medium; but all gases and liquids, and all elastic solids, transmit sound. Solids without much elasticity, such as cloth, cotton-wool, or lead, hardly transmit sound.

Sound-waves in Air.—To understand the precise nature of these, let us consider a vibrating body, say a tuning-fork, in front of an open tube (B, Fig. 21). Confining our attention to the left-hand prong of the fork, when this swings to C it compresses the air in front of it. The air, being elastic, resists the compression, and tends to expand, and therefore it compresses the air in front of it. This does the same to the next layer of particles, and so on. Thus the motion of the prong to the left causes a pulse of compression to pass along the tube. When the prong swings back from C to C′, the air next to it is relieved from pressure, and therefore, because of its elasticity, swings back too, and is followed by the particles next to it, and so on. The particles of air, therefore, spread out and the air is rarefied, and the pulse of rarefaction thus produced travels onward through the air at the same rate as the pulse of compression which preceded it. When the prong begins its next vibration another pulse of compression is produced, and this again is followed by a pulse of rarefaction, and so a succession of alternate compressions and rarefactions follow each other. What is called a *sound-wave* consists of a compression and its adjacent rarefaction.

If instead of considering the propagation of sound in a tube we consider it in the open air, the same general explanation

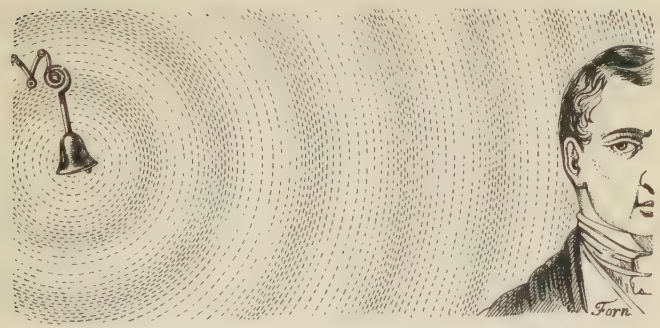


Fig. 24.—Mode of propagation of sound-waves in air. (From Ganot's *Natural Philosophy*.)

holds; but as the vibrations travel outwards at a uniform rate in all directions, therefore the sounding-body is the centre of a succession of sound-waves, which form spherical shells round it (Fig. 24). The sound-waves at last strike the delicate

membrane called the tympanum or drum of the ear, and cause it to vibrate. Its vibrations are communicated by a series of small bones to the auditory nerve and thence to the brain, and thus there is produced the sensation of sound. The ear distinguishes between *noises* and *musical sounds*. The former arise from vibrations which are irregular in their intervals; the latter result from periodic vibrations.

It should be noticed that the to-and-fro movement of the particles in an air-wave is due to the elasticity of air, and not at all to gravity.

Molecular Vibration.—It is now a generally accepted belief that the molecules of any body are in a continual state of rapid vibration within the inconceivably small distances between them. In connection with our elementary studies we learned that heat is the kinetic energy of molecular vibration. The more rapid the vibrations of the molecules of a body the hotter it becomes. If one part of a body be at a higher temperature than the rest of it, the more quickly moving particles of that part share some of their energy of motion with their more slowly moving neighbours, until in course of time the molecules of all parts are moving at the same rate, and the body is at the same temperature throughout. In short, the transference of heat by conduction consists in equalizing the rate of molecular vibration. In solids the amplitudes of the molecular vibrations are too slight to overcome the force of cohesion; in liquids the oscillations have much weakened the cohesive force; while in gases the amplitude is much greater, and the force of cohesion has been overcome.

There are also *intra-molecular vibrations*, for the atoms composing the molecules of a body are made to vibrate by heat, and by raising the temperature sufficiently the atoms in the molecules may separate and the substance undergo chemical decomposition.

Radiation-waves in the Ether.—The particles of a heated or luminous body being in a state of intensely rapid vibration, there must be a medium to carry these vibrations from one part of space to another since we see distant bodies and feel their warmth. To this medium, which we know must exist although we cannot detect it by our senses, has been given the name THE ETHER. Some of its known properties have been already stated in the *Elementary Physiography*, p. 44. It exists throughout the whole of the universe, and occupies the spaces between the molecules of all bodies. From the

great rapidity with which radiation-waves traverse it, it has been calculated that the ether is 39 million times less dense and 1278 times more elastic than air. Yet it cannot be a gas, for gases can only transmit longitudinal vibrations, while in radiation-waves the vibrations are transverse to the direction of propagation of the waves. Also a gas is compressible, whereas there is evidence that the ether is incompressible. In short, according to our present knowledge of the constitution of the ether, we must regard it as an extremely elastic, imponderable, incompressible solid, and yet so tenuous that planets and other heavenly bodies move through it without suffering any appreciable resistance. These apparently contradictory qualities are very unlike those possessed by any other kind of matter with which we are acquainted in the material universe, but it must be remembered that the ether is not material in the ordinary meaning of the word. As Sir George Stokes says—

"The ether is a substance, if substance it may be called, respecting the very existence of which our senses give us no direct information; it is only through the intellect, by studying the phenomena which nature presents to us, and finding with what admirable simplicity those of light are explained by the supposition of the existence of an ether, that we become convinced that there is such a thing."

A hot or luminous body has its particles vibrating. These molecular vibrations set up waves in the ether surrounding the body and permeating it. The waves are then transmitted from the source in straight lines in all directions through the ether at the rate of about 186,000 miles per second. The waves in the ether are, we have said, transverse ones—that is, the vibrations of the ethereal molecules are always at right angles to the direction of propagation of the wave. The molecules may oscillate in straight lines, circles, or ellipses (depending, doubtless, on the vibrations of the sender), and the paths are not in general all in the same plane, but in every case they are at right angles to the straight line in which the wave is travelling. The wave-lengths in the ether depend on the motion of the particles of the exciting body, and when the waves strike a distant body the vibrations in the ether may cause the particles of the body to vibrate, and so produce in it, according to the wave-length, light, heat, certain chemical effects, or electric and magnetic phenomena. This will be discussed more fully in the next chapter.

The Velocity of Sound in any Medium may be

obtained by Calculation.—The velocity of air-waves, or earthquake-waves, and all waves propagated by elasticity, depends on two qualities of the medium, viz. its elasticity and its density. For such waves Sir Isaac Newton gave the following rule :—

The velocity of a wave varies directly as the square root of the elasticity of the medium through which it passes, and inversely as the square root of the density.

If V stand for the velocity of the wave, E the elasticity of the medium, and D the density of the medium, then, if each of these be expressed in its proper unit, we may state the above law in symbols thus—

$$V = \sqrt{\frac{E}{D}}.$$

By means of this general equation we can calculate the velocity of sound in a solid, liquid, or gas if we know two things, viz. its coefficient of elasticity (Young's modulus in the case of solids) and its density.

It was found that the velocity of sound in gases as computed from this equation was less than the value obtained by experiment, and that to get the correct result E in the equation should be multiplied by the ratio of the specific heat of the gas at constant pressure to that at constant volume. The theoretical reasons for introducing this factor belong to the science of Sound, and cannot be explained here. The ratio of the two specific heats of air is 1·41 ; hence for air—

$$V = \sqrt{\frac{1{\cdot}41E}{D}}.$$

Important Remarks.—1. It will be observed that in these equations no mention is made of wave-length ; hence it follows that sound-waves of all wave-lengths travel with the same velocity. If this were not so, the music of a distant band would be a discordant noise.

2. Anything that affects the elasticity or density of the air, such as its hygrometric state, or its temperature, will also affect the velocity of sound through it. For example, the above equation gives the average velocity of sound in air as 1100 feet per second, but this increases at the rate of 2 feet (or 0·6 metre) per second for every degree Centigrade of rise of temperature. The velocity of sound is independent of barometric pressure, since pressure alters E and D in the same ratio.

3. The velocity of light is so great that it comes to us practically instantaneously from a distant object, and hence if a flash accompanies a sound we can calculate approximately the distance at which the sound originates. Suppose, for example, that 6 seconds elapse between seeing the

flash of a gun and hearing the report, then the distance of the gun from us is about 6600 feet. In the same way the distance of a thunder-cloud may be estimated.

Experimental Determination of the Velocity of Sound in Air.—1. A very simple method was that adopted by several French scientists in 1822. Two elevated stations near Paris, and 61,045 feet apart, were chosen, and the method consisted in measuring at one of the stations the interval that elapsed between the flash and report of a cannon fired at the other station. Hence the observers at each station were furnished with a chronometer and a six-pounder. A cannon was fired at the stations alternately to get rid of the disturbing effect due to the wind, which may not only retard or accelerate the passage of sound, but also deflect the waves out of their straight path. As the average of many observations, it was found that the report took 54·6 seconds to travel from the one station to the other; hence, dividing the distance by the time, they got—

$$\text{velocity of sound in air} = \frac{61045}{54{\cdot}6}, \text{ or } 1118 \text{ feet per second.}$$

The temperature of the air at the time of the experiment was 16° C.; hence *the velocity of sound in air at* 0° *C. is* 1118 − 32 *or* 1086 *feet per second. This is equivalent to* 332 *metres per second.*

2. The velocity of sound in air can be determined even in a class-room by measurement of the length of a tube that resounds to a tuning-fork of known pitch. This method, although simple, requires some preliminary explanation for those who have not studied elementary acoustics:—

Explanation of Resonance.—If a stretched wire be plucked its sound is scarcely audible, but if the ends of the wire be attached to a wooden or metal board, the latter vibrates in sympathy with the wire and greatly reinforces its sound. Hence the sounding-board is an important part of the piano, violin, etc. The reinforcement of a sound by the sympathetic vibrations produced by it in a neighbouring body is called *resonance*. The sound of a tuning-fork may be greatly strengthened by a column of air of suitable length vibrating in unison with it.

Expt. 24.—Sound a fork, and hold it over the mouth of a tall empty cylindrical jar (Fig. 25), and pour water slowly down the inside of the jar. Observe the effect on the loudness of the sound.

As the column of air in the tube is shortened, the sound swells out to a maximum, and then grows weaker if the air-column is further decreased. The explanation of this is as follows: When the prong of the fork swings from A to B, it compresses the air on that side, and a condensation travels down the jar till it reaches D, and is then reflected back again. If CD is the proper length, then the compression returns to C just at the moment that

the prong is going to swing from B to A and thus compress the outside air, and in that case the compression which is just emerging from the jar will increase the compression of the outside air and swell the sound.

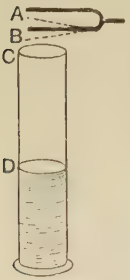


FIG. 25.—Experiment to illustrate the resonance of a column of air.

But when the prong swung from B to A, this took the pressure off the air in the jar, and therefore caused a rarefaction which travelled down the jar and back again to C, which it reached just in time to combine with the rarefaction of the outside air caused by the prong swinging back again from A to B. Thus when the column of the air is of the proper length, its compressions and rarefactions strengthen those produced in the outside air by the fork, and so increase the sound. But when the air-column is a little shorter or longer than this, the waves in it do not return to the mouth of the jar at the exact moment for combining with those outside, and therefore the sound is not strengthened.

The compression travelled from C to D and back again, and also the succeeding rarefaction similarly travelled down the tube and up again, so that in the interval of time between the beginning of one compression and the next one the distance CD was traversed four times. But from the beginning of one compression to the next is a wave-length; hence *the length of a sound-wave is four times the length of the column of air closed at one end which reinforces it.*

Using this principle, we may find the velocity of sound thus:

EXPT. 25.—Take an open glass tube about 50 cms. long and about 5 cms. in diameter, and bind a millimetre scale to it, and insert one end of the tube in a wider vessel nearly full of water (Fig. 26). Sound a tuning-fork whose pitch is known (say C, which vibrates 256 times per second), and hold it with its prongs in a vertical plane and immediately over the upper end of the tube. Alter the length of the air-column in the tube by raising and lowering the latter, until the point of maximum resonance is found, and then measure the length of the air-column in millimetres. Repeat the experiment several times, and take the average of the results.

FIG. 26.—Experiment to determine the velocity of sound in air.

Suppose sound travelled from a point A to a point B in a second, then if v were the velocity of sound per second it would be equal to the distance AB. Also, if n were the vibration-frequency of the waves, and l their wave-length, then there would be n waves, each of length l, between A and B; therefore AB would also be equal to $n \times l$, and hence—

$$v = nl$$

that is, the velocity of sound per second is equal to the number of vibrations per second multiplied by the wave-length.

But we have explained that the length of the sound-wave is four times the length of the column of air, in a tube closed at one end, that resounds to it. Calling this latter length l', then—

$$v = 4nl'$$

and as n is known and l' can be measured as in Expt. 25, the velocity of sound is obtained.

Velocity of Sound in Water.—One of the best experiments to determine this was that of Colladon and Sturm, on the Lake of Geneva, in 1827. One observer was in one boat, and the other in another at a measured distance off. From one of the boats a bell was hung under the water. A lever was attached to the upper part of a long hammer that struck the bell, so that at the instant the bell was struck a little gunpowder on the boat was ignited by a light at the upper end of the lever. The observer on the distant boat held an ear-trumpet to his ear, the large mouth of the trumpet being at the same depth in the water as the bell, and directed towards it. By means of a chronometer he observed the interval between seeing the flash and hearing the sound; and then, on dividing the distance apart by the time, the velocity of sound in water was obtained. The result was 4708 feet (1435 metres) per second, the water being at a temperature of 8° C.

The Velocity of Sound in Solids is equal to the square root of the ratio of the elasticity of the solid to its density (p. 52). In every case it is much greater than in air. Biot experimented with a length of 951 metres of cast-iron water-pipes in Paris. He caused a pistol to be shot across one end of the tube while his ear was applied at the other, and from the result he found the velocity of sound in cast-iron to be 10,830 feet per second, or almost ten times that in air.

The Velocity of Ether Waves has been determined in several ways, but we have only space to briefly describe two astronomical methods and one experimental method.

1. *Roemer's Method, by Observations of the Eclipses of Jupiter's Satellites.*—Jupiter has five moons or satellites revolving round it, and as the planes in which the earth and Jupiter move round the sun and the planes in which the satellites revolve round Jupiter very nearly coincide, the moons pass behind Jupiter and become invisible once in every revolution. Roemer, a Danish astronomer, in 1675 observed

that the interval between successive eclipses of a satellite was not always the same; that the interval became shorter as the earth was approaching Jupiter, and longer as it was receding; and that the period between successive eclipses of a satellite was 996 seconds shorter when the earth was nearest Jupiter than when on the opposite side of its orbit from that planet. From this Roemer concluded that the passage of light was not instantaneous as had hitherto been supposed, and that light must take 996 seconds to cross the earth's orbit. This will be better understood from Fig. 27. Let J represent Jupiter with

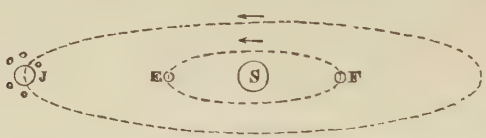


FIG. 27.—To explain the determination of the velocity of light by observations of the eclipses of Jupiter's satellites. S is the sun; the larger orbit is that of Jupiter, and the smaller orbit is the earth's.

his five satellites, E the position of the earth when nearest to Jupiter, and F its position when on the opposite side of the sun from Jupiter. Then when the earth is in the first position, the light has only to travel from J to E; and when it is in the second position, the light has to travel from J to F; and light takes 996 seconds less time to travel from J to E than from J to F. The difference in distance is EF, which is 185,000,000 miles (twice 92½ million miles, the distance of the earth from the sun); and as light takes 996 seconds to travel this distance, its velocity is 185,000,000 ÷ 996, or nearly 186,000 miles per second.

2. *Bradley's Method, by Aberration of Light.* — In 1727 Bradley, the Astronomer Royal, while making a series of observations on fixed stars, discovered that each one appeared to describe a small orbit round its actual position in the course of a year. This apparent displacement of heavenly bodies is known as "aberration." Some illustrations will suggest the explanation:—

On a calm rainy day, a person standing still holds his umbrella vertically in order to protect himself. But if he walks he must hold it forward, and more so the faster he walks. Thus while he is walking the rain does not seem to be coming in its true direction, and he rightly concludes that this *aberration*, or wandering, of the raindrops from their normal path is due to his motion while the drops are falling. Also, if he knew the rate at which he

was walking, and the angle at which the raindrops were striking him, he could calculate the velocity with which the drops were falling.

Again, suppose a shot to be fired from a cannon, C (Fig. 28), against a ship, AB, in rapid motion. If the vessel were at rest the shot would pierce the two sides at D and E; but during the time the shot was passing from one side to the other the ship moved a small distance and the farther side was pierced at F, and from the position of the two holes the shot will appear to have come from C'. This apparent change in the direction of the shot depends upon two velocities, for if the velocity of the shot had been greater the difference in position of C and C' would have appeared less, and if the velocity of the ship had been greater C' would have seemed farther ahead of C. Also, if the velocity of the ship had been known, and the angle FDE, then the velocity of the shot could have been calculated.

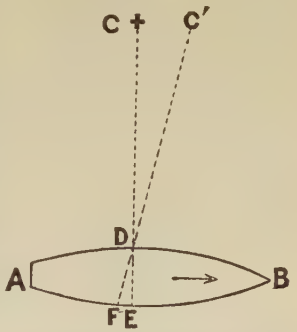


FIG. 28.—To illustrate the apparent alteration of direction owing to a combination of two motions. (From Watson's *Text Book of Physics*.)

We can now understand why every star seems to describe a little ellipse round its true position once a year. The reason is, that during the time that the rays of light from the star are travelling from D to E (Fig. 29) down the tube of the observing telescope, the latter is carried forward at the rate of $18\frac{1}{2}$ miles a second by the motion of the earth in its orbit; and this causes the rays to fall towards the hinder side of the tube, just as the direction of the shot seemed displaced in the ship (compare Figs. 28 and 29). Hence, in order to see the star in the centre of the field of view, the telescope must be tilted forward into the direction FDC', so that the star does not seem to be at C but at C' ahead of it. We may therefore define *aberration of light as the apparent displacement of a star owing to the combination of the velocity of light with the velocity of the earth in its orbit.* In the course of a year, therefore, as the earth moves round in its elliptical orbit, a star viewed through a telescope always seems ahead of its actual position in the direction in which the earth is moving at the moment, and all the apparent positions of the star during the year lie on the circumference of a little ellipse (Fig. 30). The star is really at the centre C, and as the major axis of the ellipse is always found to be 41″ of an arc, therefore the star always appears to be 20″·5 away from its true place—that is, the arc CC' is 20″·5, or the angle FDE is 20″·5. But light travels the distance DE while the earth carries the

telescope the distance FE, so that DE represents the velocity of light on the same scale as EF represents the velocity of the earth in its orbit. But if in any given angle we drop from a

FIG. 29.—To illustrate why heavenly bodies viewed through a telescope seem ahead of their true position in the direction in which the earth is moving.

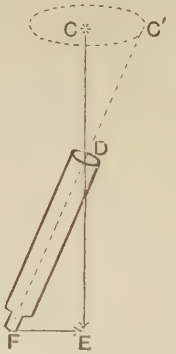


FIG. 30.—Diagram illustrating the method of finding the velocity of light when we know the velocity of the earth in its orbit, and the constant of aberration.

point in one arm a perpendicular to the other arm, then, whatever point we take, the ratio of the perpendicular to the base is constant and is called "the tangent of the angle." The tangents of different angles are given in mathematical tables; for example, the tangent of 20″·5 is almost $\frac{1}{10000}$.

Therefore in Fig. 30—

$$\frac{\text{perpendicular FE}}{\text{base DE}} = \text{tangent FDE}$$

that is—

$$\frac{\text{velocity of earth in its orbit per second}}{\text{velocity of light per second}} = \text{tangent } 20''{\cdot}5$$

therefore—

$$\frac{18\frac{1}{2} \text{ miles}}{\text{velocity of light per second}} = \frac{1}{10000}$$

whence—

$$\text{velocity of light per second} = 18\tfrac{1}{2} \text{ miles} \times 10{,}000$$
$$= 185{,}000 \text{ miles.}$$

3. *Foucault's Method* (1850) utilizes the principle that when a mirror rotates through any angle, a ray of light reflected from it is deflected through twice that angle. Fig. 31 is a diagram of his apparatus. A bright light was sent through a narrow slit at S to a plane mirror, R, which could be rotated rapidly in the direction shown by the arrow. When the mirror R was at rest, the rays reflected from it were focussed by the lens L on to a fixed plane mirror M, whence they were reflected and exactly retraced their path back to the slit S. But when R was set in rapid rotation, it altered its position during the time that the rays were travelling from R to M and back again, and therefore they were not reflected back to S, but were deflected in the direction of the rotation to S', through twice the angular distance described by R during the time required by the light to travel twice the distance between the mirrors. The angle of deflection of the rays from S to S' was measured. Half this was the angle that R turned through while light was passing from the one mirror to the other and back again. But the rate at which R was rotating was known, therefore the time it took to rotate through this angle was known; that is to say, the time taken by light to travel twice the distance RM was known, and from this the velocity of light was found to be 186,330 miles per second.

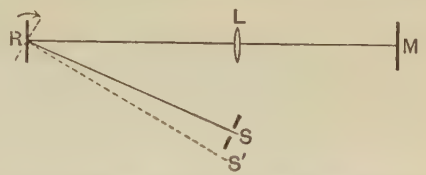


FIG. 31.—Principle of Foucault's apparatus for determining the velocity of light.

Still more recently Professor Newcomb, by the same method, has got practically the same result, viz. 186,328 miles a second, and such care was taken that it is believed that this can scarcely be more than twenty miles a second wrong either way.

QUESTIONS.

1. Describe the nature of the movements of waves in water, sound-waves in air, and radiation-waves in ether.

2. Describe the general nature of wave-motion. What are *longitudinal waves*, and what are *transverse waves*?

3. Compare the vibrations which produce sound and light respectively, stating in what respects they agree, and in what respects they differ.

4. If a tube connects distant parts of a building, words spoken into one end can be distinctly heard at the other. Explain the transmission of the

sound, and give the reason why it is heard louder than if made in the open air.

5. Compare the velocity of water-waves, sound-waves, and waves of ether. Compare also the wave-form in these cases, and explain the terms *wave-length*, *phase*, *amplitude*, *wave-frequency*, *period*.

6. How can it be shown that a material medium is required for the transmission of sound?

7. State what you know concerning the velocity of sound-waves and light-waves. How do the waves producing violet light differ from those producing red light?

8. How can the velocity of sound be determined by an experiment with a tuning fork of known pitch, and a glass cylinder into which water can be poured?

9. From the definitions of velocity, wave-length, and wave-frequency, show that velocity = wave-length × wave-frequency.

10. If the velocity of an air-wave is 1100 feet per second, and its wave-length 4 feet, what is its wave-frequency?

11. If air is confined so that it cannot expand, how will the speed of an air-wave be affected when the air is heated?

12. One day when the temperature was 30° C., I counted 7 seconds between a lightning flash and the thunder. How far away did the lightning occur?

13. Give a reason why sound should travel faster at the summit of a high mountain than at its base, and also a reason why it should not.

14. Describe carefully two methods of determining the velocity of light.

CHAPTER V.

RADIATION.

The Visible Portion of the Spectrum. — From his study of elementary physiography, the reader should be already familiar with many facts concerning the refraction and dispersion of radiation (see *Elementary Physiography*, pp. 79–82). He will have learnt that sunlight (and the same is true of all white light) is a compound of many colours, roughly distinguished as red, orange, yellow, green, blue, and violet, with every gradation of shades between them for only a few of which have we names at our command; that the different colours have different refrangibilities, red being the least refrangible, and violet the most; that the decomposition of light, or the separation of rays of different refrangibilities by passing a very narrow beam of the light through a prism, is called *dispersion;* that the coloured band (called the spectrum) produced in this way is just an image of the slit in all the different colours present, and the images are so close to each other as to be absolutely continuous; and that to obtain a pure spectrum, namely, one in which there is no overlapping of adjacent colours, we must pass the light first through a very narrow slit, and then through the prism placed with its edge parallel to the slit and in the position of minimum deviation or refraction.

We have now to explain somewhat more fully how the refraction and dispersion are produced.

Refraction explained.—In the last chapter we said that according to Newcomb the speed of light in space is 186,328 miles, or very nearly 300 million metres, per second. It is a little less in air, and still less in transparent liquids and solids. It is because radiant energy is propagated at different rates in different substances that it is bent or *refracted* out of its original direction in passing from one transparent medium into another. For example, let AB (Fig. 32) represent the

surface of water, and let W be an ether-wave passing through air. The wave-front is at right angles to the direction of propagation, therefore it may be represented by *cd*. When this wave-front reaches the water, the point *e* of it enters the water first. But experiments prove that the velocity of light in water is three-fourths of that in air, so that when *f* has reached *h*, *e* has only gone to *g*, three-fourths as far. *hg* is now the wave-front, and the wave travels through the water at right angles to it to W′, and has therefore been deflected towards the normal XY. Had it been proceeding from water into air, it would have been deflected from W′ to W, away from the normal.

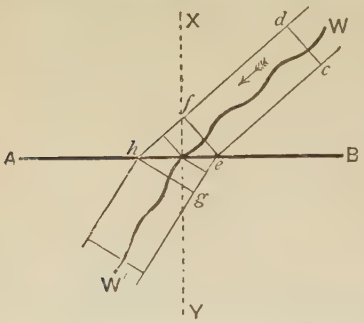


FIG. 32.—To explain the refraction of radiation in passing from one medium into another of different density.

Dispersion explained.—All kinds of radiations travel at the same rate in air, but not in denser media such as transparent liquids and solids like water and glass. In passing from a rarer into a denser medium, the longest ether-waves are least retarded, and therefore, as explained above, least bent out of their original direction, while the shortest waves are most retarded, and therefore most turned out of their course.

Physicists have computed the wave-lengths in ether that produce the different colours; that of red light has been found to be about 0·00008 cm., that of violet light about half of this, or 0·00004 cm.,[1] and the wave-lengths of all the other colours lie between those limits. Hence, if a very narrow beam of compound light be passed through a prism, the constituent colours will be separated; if there is any red in the beam it will be least

[1] It has been explained on p. 54 that $v = nl$, or $n = v \div l$, that is to say, the number of waves per second is equal to the velocity divided by the wave-length. But since light, whatever its colour, travels with the same velocity through space, namely 300 millions of metres a second, therefore the number of ether-waves per second that produce the sensation of red light is 300,000,000 m. ÷ 0·00008 cm., or roughly 400 millions of millions (400,000,000,000,000), and since the wave-length of violet is about half that of red, the sensation of violet light is due to almost 800 millions of millions of ether-waves reaching the eye in one second. The other colours of the spectrum are intermediate in wave-frequency.

refracted, and violet most refracted, and between those limits all the other colours will be arranged according to their wave-lengths.

After a compound light has been thus analyzed, it is impossible to further decompose any of the colours. If, for instance, pure violet light be allowed to pass through another prism, it is merely refracted but not changed in character (Fig. 33).

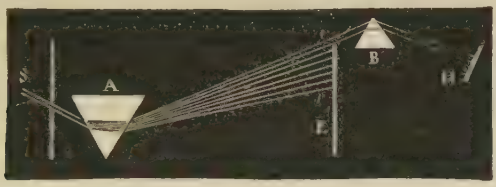


FIG. 33.—Indivisibility of the colours of the spectrum. In the diagram the violet is represented as passing through a small aperture in the screen E to a second prism, B, which merely refracts it. (From Ganot's *Physics*.)

Explanation of Colour.—Colour in light is analogous to pitch in sound. Just as air-waves of different lengths are recognized by the ear as sound of different pitches, so ether-waves of different lengths falling on the retina produce different sensations, the longest waves awakening the sensation of red, and the shortest that of violet. That which we call white light is due to a mixture of all possible wave-lengths between 0·00008 and 0·00004 cm., and just as a mixture of sounds of every audible pitch would produce the impression of no particular pitch, so a mixture of every visible colour produces the sensation of white light which is uncoloured.

The Invisible Portions of the Spectrum—the Infra-red and Ultra-violet.—Just as the ear is only sensitive to air-waves whose lengths lie between certain limits, so the eye has only a certain range of sensibility, and if ether-waves be longer than the red or shorter than the violet they do not affect our retina. If a sensitive thermopile connected with a galvanometer be placed beyond the red end of the visible spectrum, it will show that there are heat-rays there. These invisible rays extending for some distance beyond the red are called the *infra-red* (or *ultra-red*) *rays*, and the heating energy of the beam is chiefly due to them. Similarly, if a photographic plate be placed in the region beyond the violet, it will be chemically acted upon, and since these non-luminous vibrations are chemically *active*, they are called the *actinic* or *ultra-violet rays*.

Ether-waves while traversing the ether present no essential differences. They are all transverse waves differing only

in frequency, and hence also in wave-length. The wave-frequencies of the entire spectrum range from 40 millions of millions per second (the lowest invisible heat-rays according to Langley) to 40,000 millions of millions per second (the highest actinic rays), the extreme visible limits being, as we have already said, 400 and 800 millions of millions per second.

The Illuminating, Thermal, and Chemical Effects of the Spectrum.—In order to examine the radiations of different wave-lengths, we must effect the dispersion by means of a prism which will transmit if possible all, and absorb none, of the radiant energy. No substance is transparent to all radiations, but glass transmits nearly all the luminous rays, rock-salt practically all the ultra-red, and quartz all the ultra-violet, hence prisms of these three substances are used for examining the kind of radiation they freely transmit.

1. *Illuminating Effect.*—As we said in the last section, only waves in ether with a wave-frequency between 400 and 800 millions of millions per second can produce the sensation of light. The middle curve in Fig. 34 shows the intensity of light

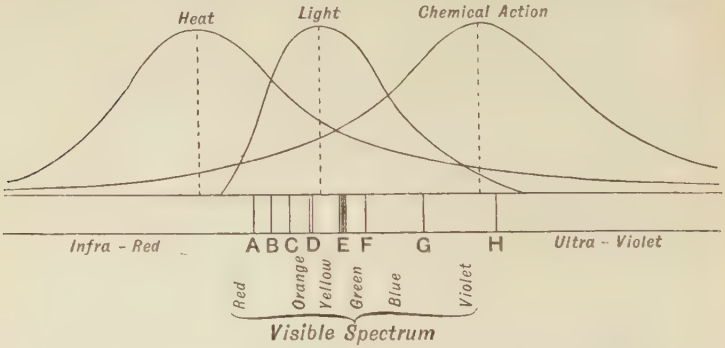


FIG. 34.—Curves showing the luminous, thermal, and chemical intensities at different parts of the spectrum. The greatest illuminating effect is about the yellow part of the spectrum, the maximum heating effect is in the ultra-red portion of the spectrum not far beyond the red, and the greatest chemical effect is near the violet.

in the different parts of the spectrum according to the experiments of Fraunhofer and of Herschel, the intensity at any part being proportional to the length of the perpendicular to meet the curve from that part of the horizontal line. The diagram shows that the greatest luminous effect is in the yellow part of the spectrum.

2. *Thermal Effect.*—By using a prism of rock-salt instead of glass as the refracting substance, and allowing the radiations to fall upon the face of a delicate thermopile, it is found that the greatest heating effect is in the ultra-red about as far from the red as the latter is from the yellow; and that thermal rays extend away down into the infra-red to wave-lengths ten times as long as those that produce red light, and hence the whole of the heat-curve cannot be shown in the diagram. The heat of the spectrum is not, however, confined to the infra-red, for if the luminous rays or the chemical rays be allowed to fall upon a surface covered with lamp-black, they are absorbed and transformed into heat. Hence, as shown in the figure, the heat-curve extends into the highest portions of the ultra-violet spectrum.

3. *Chemical Effects.*—Ether-waves can produce chemical action in various ways. They can chemically change the chloride of silver (which is white) into a black compound, and it has been found that the blackening effect is greatest in the violet portion of the spectrum, and diminishes very slightly for some distance into the ultra-violet. Again, vegetable colouring-matters fade in light; and hydrogen and chlorine combine with explosive violence in sunlight. But perhaps the most important instance of the chemical action of sunlight is that in which it enables the green colouring-matter, chlorophyll, of plants to decompose the carbon dioxide of the atmosphere, the carbon being retained to form the tissues of the plant, and the oxygen being given back to the atmosphere.

The chemical part of the spectrum extends away up into the ultra-violet to parts with only one-fiftieth of the wave-length of the violet. But while the chemical action of the spectrum resides chiefly in the ultra-violet, it is not confined to that part, but extends with diminishing intensity through the luminous into the infra-red portion of the spectrum (see Fig. 34). Indeed, by using suitable chemicals, all parts of the spectrum have been photographed, from the lowest infra-red to the highest actinic rays known to exist.

We must reiterate the warning with which we closed the last section, against thinking of radiations in the ether as of three distinct kinds—thermal, luminous, and chemical—for we have just shown that these different effects depend largely on the qualities of the substance on which they fall. All parts of the spectrum can be made to produce heat or chemical action by properly choosing the sensitive surface.

The Spectroscope is an instrument for the observation of

spectra. It consists essentially of three parts—a *prism*, to cause the dispersion; a *collimator*, to bring the light to the prism

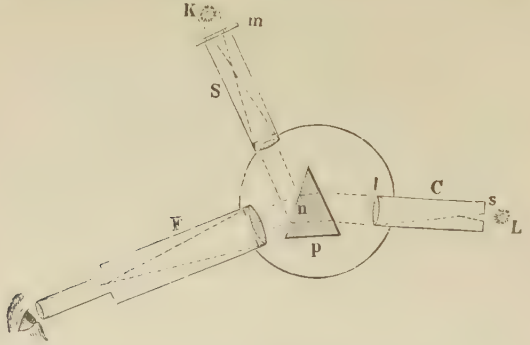


Fig. 35.—A spectroscope in plan.

for examination; and a *telescope*, to magnify and examine the spectrum produced. The collimator (C, Fig. 35) is a metal

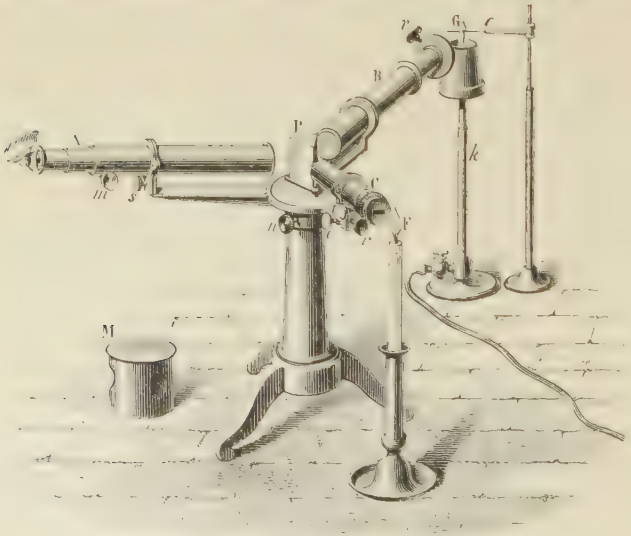


Fig. 36.—The spectroscope. (From Ganot's *Physics*.)

tube having at one end, *s*, a slit whose width can be varied (by

means of screw *r*, Fig. 36). A narrow converging beam of the light L to be examined enters at *s*, and the point at which the beam converges is the focus of an achromatic lens, *l*, at the other end of C. This lens renders the diverging rays parallel. The parallel rays then fall on a glass prism, *p*, which has an edge parallel to the slit *s*. F is a small telescope which can be moved so that any part of the spectrum can be examined.

In examining a spectrum it is necessary to measure the distances between different parts of it, and one method of doing this is as follows: There is a metal tube, S, having at one end, *m*, a scale photographed on glass. This is illuminated by a light, K, and the rays from the scale are made parallel by the lens at the other end of S. These parallel rays from the scale strike the prism at such an angle as to be reflected from its surface into the telescope. An observer looking through F then sees an image of the scale lying along the edge of the spectrum, and thus he can measure the distance between lines in the part of the spectrum then under examination.

Absorption of Wave-motion—Selective Absorption.—For the sake of fully understanding what is said in succeeding parts of this chapter about absorption-spectra, and especially about the Fraunhofer lines in the sun's spectrum, we shall briefly study the absorption of air-waves and of ether-waves.

Absorption of Sound-waves.

EXPT. 26.—Take two large tuning-forks that sound in unison and are mounted on sounding-boxes. Place the boxes in the same line and with their open mouths near each other. Now make one of the forks sound, and then stop its vibrations by taking hold of it, and listen to the other. Next put the forks out of unison by loading the prongs of one of them with a little wax, then repeat the experiment and listen to the result.

In the first case, the fork which was at rest vibrated in sympathy with the other because it was struck by air-waves having the same frequency as those which it could itself produce. Similarly, if we gently pressed down several of the keys of a piano so as to take the pressure of the dampers off the wires without sounding them, and then opened the top of the piano and sang into it a note corresponding to one of the wires, we would, on ceasing to sing, hear that wire vibrating, and none of the others would be affected. In short, the law is that *bodies only absorb vibrations of the same wave-length as those which they are capable of producing*. This is a general principle, as we

shall see, for all kinds of wave-motion, and is termed *selective absorption.*

Absorption of Radiation.—1. *Absorption of Light-waves.*

Expt. 27.—Place on the stage of an optical lantern a piece of clear glass all covered with brown paper except a very narrow vertical slit, and produce a long spectrum of the slit by a carbon disulphide prism. Then place a piece of red glass between the slit and the prism, and note the change in the spectrum. Repeat with a blue glass (cobalt glass).

The red glass extinguished the blue end of the spectrum; that is to say, it absorbed the blue rays. If a piece of red glass were made to glow in a dark room, it would have a bluish tinge, and hence *the red glass absorbed the rays which it was itself capable of emitting.* Similarly with the blue glass.

Expt. 28.—Put some common salt on the wick of an ignited spirit-lamp, and observe the yellow colour of the incandescent sodium vapour. Analyze a very narrow beam of the light by means of a prism of high dispersive power, and observe the spectrum. Now place a lime-light behind the spirit-lamp, so that its intense white light shines through the sodium-tinged flame, and note the change in the spectrum.

The explanation is that the yellow tinge of glowing sodium vapour is due to vibrations of two wave-lengths in the ether, and as these are separated by the prism, the spectrum is two bright yellow lines very close to each other, so close, indeed, as to coincide unless high dispersive power is used. The spectrum of lime-light we know, from our elementary studies, to be a continuous band from the red to the violet. But when the lime-light is passed through sodium vapour, we find its spectrum crossed by two black lines exactly in the position previously occupied by the double sodium line, showing that *when luminous rays of all possible wave-lengths are passed through a gas, it only absorbs the vibrations of the same wave-length as it itself is capable of producing when luminous.*

When ether vibrations are absorbed in this way by a substance, the energy of the ether is transferred to the molecules of the substance and causes them to vibrate; that is, the energy is transformed into heat. It is another instance of the degradation of energy.

2. *Absorption of Heat-waves—Diathermancy.*

Expt. 29.—Focus the rays from the sun or the electric arc-light by means of a large biconvex lens of rock-salt. A little beyond the point at which the light is focused place a piece of paper. It is ignited. If a piece

of platinum foil or charcoal be placed in the same position, it may be made to glow. Repeat the experiment, using a glass lens instead of rock-salt.

EXPT. 30.—Take a thin flat cell with glass sides, and into it put a strong solution of iodine in carbon disulphide, and repeat the above experiment with this cell between the rock-salt lens and the source of light. No light now gets through the lens, but the heating effects are undiminished. Repeat the experiment with water in the cell. The light gets freely through, but no heat.

Substances such as glass, rock-salt, and water, which allow luminous rays to pass through, are said to be *transparent;* those which do not are called *opaque*. Similarly, bodies which allow heat-rays to pass through them (not merely ultra-red rays, but also the heat-rays associated with the luminous and ultra-violet radiations) are called *diathermanous*. Bodies which do not allow heat-rays to pass through them are said to be *adiathermanous*, or *athermanous*. From the foregoing experiments we see that rock-salt is both transparent and diathermanous; indeed, it is the most diathermanous of all known solids or liquids. A solution of iodine in carbon bisulphide is opaque, but diathermanous. Water is one of the most adiathermanous substances. The behaviour of glass towards heat-rays is peculiar, for it is of low diathermancy towards the ultra-red vibrations but allows the heat-rays resident in the luminous and ultra-violet portions of the spectrum to pass through it. Hence glass is well adapted for fire-screens since nearly all the heat of a fire belongs to the ultra-red, but it would be of little use as a screen from the sun's heat, for although it would stop most of the ultra-red vibrations, yet the luminous rays, being much more powerful than in the case of a fire, would pass through, and a great deal of heat would pass through with them. For example, the glass of a conservatory allows the heat associated with the luminous rays of the sun to pass through and heat the objects in the interior. These, being warmed, radiate the heat, but they are at a dark heat and hence the glass stops their rays. Thus a large part of the sun's heat can get into the greenhouse but cannot get out again, and so the temperature of the air inside rises.

Diathermancy of Dry Air and Other Gases—Absorption of Infra-red Radiation by Water-vapour and its Effects.

EXPT. 31.[1]—CDEF represents the bulb of an air-thermoscope, consisting

[1] This pretty lecture-table experiment is from *Physics, Experimental and Theoretical*, by Dr. Jude and M. Gossin (Chapman & Hall).

of a horizontal glass cylinder whose two ends are closed by two plates, CD and EF, of rock-salt, and cemented air-tight. H is a small piece of charcoal. A beam of rays R from the sun, or other strong source of heat, is focused at G inside the bulb by a rock-salt lens, LL. Observe that the liquid is hardly depressed in the stem, showing that the heat-rays are not absorbed by the air. Now shift LL so as to focus the rays on H. The latter absorbs the heat, and the liquid is forced down.

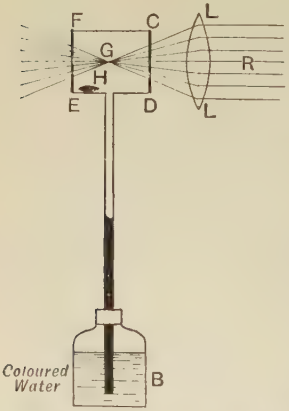


FIG. 37.—Diathermancy of air.

Ether is the only perfectly diathermanous substance, but air and other "permanent" gases are highly diathermanous when dry. It is because of the dryness of the air at the top of a mountain [1] that a person in the sunshine there may have his skin blistered by the sun's rays, although the air itself is bitterly cold. The dry air there, being diathermanous, allows the sun's rays and the rays rising from the warm surface of the earth to pass through unhindered; the air, therefore, is not heated, and may be so cold that water may be freezing in the shade of a rock beside the person. Similarly, in Arctic regions the sun's rays are sometimes warm enough to melt pitch, although the air is many degrees below freezing-point.

Water-vapour behaves exactly like glass in being adiathermanous to dark heat-waves. Tyndall showed from experiments that ordinary air, because of the water-vapour in it, absorbs on an average 72 times as much heat from the sun as dry air does. Moreover, just as in the case of the greenhouse, the sun's luminous rays warm the earth's surface, which, therefore, gives off heat by radiation. But they are dark heat-rays that are given off, and, the water-vapour in the atmosphere being athermanous to them, they are stopped at about ten feet from the earth's surface. The aqueous vapour therefore acts like a blanket, preventing the earth from cooling too much during the sun's absence by night. But for this, water would be frozen

[1] Aqueous vapour is most abundant in the part of the atmosphere near the earth's surface. It has been calculated that one-half of the total quantity of water-vapour in the air is contained in the lowest 6000 feet of the atmosphere.

by night, plant-life would be destroyed, and the earth would be uninhabitable.

It should be stated, however, that recent investigations cast some doubt on the athermancy of aqueous vapour, and even seem to show that it is as diathermanous as dry air. It is maintained by Lord Kelvin that the protective action of the water-vapour in the atmosphere is not due to its athermancy, but to its very great capacity for heat. For this reason it cools very slowly, and therefore the vegetation and other objects in contact with it are made also to cool slowly.

Different Kinds of Spectra.—In connection with the foregoing experiments, the student will have seen the spectrum of the lime-light, of sodium vapour, and of lime-light shining through sodium vapour. The lime-light spectrum contained all the colours from red to violet without any break in their continuity; such spectra are called *continuous spectra*. The spectrum of sodium consisted of two bright-coloured yellow lines; such spectra are called *bright-line spectra*. In the case of lime-light shining through sodium vapour, the spectrum was crossed by two fine dark lines produced by absorption; such spectra are called *absorption spectra*.

Hence for convenience spectra are classified as follows:—

1. Radiation or Emission Spectra, produced by the light of incandescent solids, liquids, or gases. There are two classes of radiation spectra according to the physical condition of the radiating body—

(*a*) *Continuous spectra* are those in which the colours run continuously from the red to another colour depending on the temperature of the body. If the body is at a white heat, all the colours will be present from red to violet. An *incandescent solid* or *liquid*, or an *incandescent gas under great pressure, gives a continuous spectrum.*

(*b*) *Bright-line spectra* consist of bright lines or bright bands with blank spaces between the lines or bands. An *incandescent gas* (*unless under great pressure*) gives a spectrum of this kind. The positions of the bright lines are different for different gases.

2. Absorption Spectra are continuous spectra crossed by dark lines which run parallel to the colours. This is the kind of spectrum given by an *incandescent solid or liquid shining through a gas at a lower temperature.* The dark lines are in the same position as the bright lines of the spectrum of the gas would be. The sun's spectrum is of this kind.

These different kinds of spectra are illustrated by the coloured spectra on the slip facing this page. 1 is a continuous spectrum, 2 a bright-line spectrum, and 3 an absorption spectrum.

Explanation of the three different kinds of spectra.

1. *The Continuous Spectrum.*—The appearances seen in a spectrum are simply images of the slit of the spectroscope in the colours corresponding

to all the different wave-lengths present. In the white light of incandescent solids and liquids every possible wave-length is present, hence there is a multitude of images of the slit of the spectroscope ranged side by side and so close together that no break in the spectrum can be distinguished.

2. *The Bright-line Spectrum.*—When a substance is in the gaseous state, the molecules of its elements are free to vibrate in their own special way when set in motion by heat, and thus they produce waves in the ether of certain definite wave-lengths only. When sodium vapour, for example, is heated to luminosity, its particles set up vibrations in the ether of two definite wave-lengths very nearly alike (almost 0·00006 cm.), and when these are separated by means of a prism there is an image of the slit in the colour produced by each of the two wave-lengths. Hence the spectrum of incandescent sodium vapour consists of two yellow lines so close together that they can only be separated by using a prism of large dispersive power. For a similar reason the spectra of other gases consist of one or more bright lines.

3. *The Absorption Spectrum.*—Suppose that in Expt. 26 (p. 67) there had been a great many tuning-forks of the same pitch as the one that was made to sound, then it would have given a share of its energy to each, and, if there had been a sufficient number, silence would have been produced, for each one would have absorbed a part of the energy, but not enough, because of their number, to make it audible. Furthermore, if a chord had been sounded containing the note of the forks, all the notes of the chord would have been heard except the note of the same pitch as the forks, and this one would be missing because of its having been absorbed. Hence when, in Expt. 28 (p. 68), white light, which includes rays of all wave-lengths, was sent through sodium vapour, the particles of sodium were set in vibration by the two waves about 0·00006 cm. in length, which therefore had their energy absorbed. All the other waves got through and produced their images of the slit of the spectroscope, and two blank lines marked the position of the images that would have been produced by the missing yellow rays (see in the coloured spectra the two dark lines in the solar spectrum corresponding to the two bright lines in the sodium spectrum). In a similar way, the vapours of all other elements absorb their own particular wave-lengths from light passing through them.

Examples of the different kinds of spectra.

1. In the *incandescent electric lamp* the light is produced by a white-hot solid (a glowing carbon filament), therefore its spectrum is continuous.

2. In the *electric arc* the light is produced partly by the white-hot points of the carbon rods, and partly by white-hot carbon gas between the points. Hence the spectrum of the carbon points is continuous, whereas the spectrum of the part between the points consists of the bright lines of carbon vapour.

3. *Ordinary coal-gas* consists chiefly of a mixture of hydrogen and compounds of carbon. When gas is ignited, the oxygen of the air unites with the hydrogen of the gas to form water-vapour. The heat of this chemical combination makes the particles of carbon white-hot, and they unite with the oxygen of the air to form carbon dioxide. The products of the action are therefore water-vapour, carbon dioxide, and carbon (in the form of soot).

It will be noticed that in a gas-flame there are two parts. The lower blue part consists of faintly luminous gas, and therefore gives a faint spectrum of the bright lines of hydrogen and the other elements of coal-gas. It is, however, the upper white part of the flame that gives the light, and as it consists of white-hot solid particles of carbon, its spectrum is continuous.

4. A *candle-flame* consists similarly of two parts. If the slit of a

spectroscope be directed towards the blue part at the base of the flame, we find the spectrum to consist of two or three bright flutings of carbon vapour, whereas the upper and more luminous part of the flame gives a continuous spectrum, for there we have incandescent solid carbon particles.

5. The spectrum of the *flame of an oil-lamp* is continuous, because the luminosity is produced by white-hot particles of carbon.

6. When *a match* burns, the carbon of the wood is made white-hot by uniting with the oxygen of the air to form carbon dioxide. Also particles of carbon rise through the flame and are made white-hot. Since the light is produced by the white-hot wood and the white-hot particles of carbon in the flame, its spectrum is continuous.

7. The student will already know that *lightning* is just the air along the track of the discharge made white-hot. Hence its spectrum consists of the bright lines belonging to incandescent air, and pre-eminently those of nitrogen, but also of the other constituents of air, such as oxygen, carbon dioxide, water-vapour, etc.

The Solar Spectrum.—The spectrum of the sun is not a continuous one; several thousands of very narrow black lines break the continuity of the colours. These lines are called the *Fraunhofer lines*, after the German scientist who first made a chart of their position in the spectrum. Only a very few of them are shown in the coloured spectrum facing p. 71. Fraunhofer designated the most prominent dark lines by the first eight letters of the alphabet, the A line being in the red end of the spectrum, and the H in the violet (see Fig. 34). The Fraunhofer lines occupy fixed positions, and therefore they are important for locating points in the spectrum exactly, and also for telling of what chemical elements the sun is composed.

The Fraunhofer lines are produced by absorption. Before the light from the bright surface of the sun (called the photosphere) reaches us it has to pass through the vapours which surround the sun, and also through the earth's atmosphere, and these absorb, as was explained in the section before the last, the particular vibrations they would emit if incandescent.

The Infra-red and Ultra-violet Portions of the Solar Spectrum.—Beyond the red end of the visible spectrum of the sun is an extensive region of invisible heat-rays. Indeed, the length of the infra-red spectrum has been shown by Langley to be ten times that of the sun's luminous spectrum.

Beyond the violet, again, are the invisible actinic rays, and the length of this invisible ultra-violet spectrum is also many times that of the visible spectrum. Because of the chemical activity of the rays, photographs of this region of the spectrum can readily be taken, and they show that it is crossed by absorption lines just as in the visible spectrum. It is not so

easy to photograph the infra-red spectrum, as its chemical intensity is very feeble; but Sir W. de W. Abney has, by a special preparation of the bromide of silver, obtained good photographs of the infra-red end of the solar spectrum, which show that it is crossed by many absorption lines of vapours of metals with low melting-points, such as sodium and calcium. Indeed, by properly choosing the sensitive substance, photographs can now be taken of any part of the solar spectrum from the longest infra-red to the shortest ultra-violet rays known to exist, and this extensive solar spectrum is of the same nature throughout, namely, a continuous spectrum crossed by dark lines.

The Telluric Lines in the Solar Spectrum.—The Rain-band.—Many hundreds of the dark lines in the sun's spectrum are caused by absorption in our own atmosphere. They are called the telluric lines (Lat. *tellus*, the "earth"). That they are due to selective absorption by the earth's atmosphere is shown by the fact that they vary in number, intensity, and breadth with the varying atmospheric conditions, and that they are more strongly marked in the morning and evening than when the sun has attained his meridian altitude. Many of them are due to water-vapour. Janssen proved this by analyzing a bright light that had passed through a long cylinder full of steam, and he thus obtained lines coinciding in position with those characteristic of the spectrum of the setting sun. The most prominent of these lines is a group in the yellow, between the C and D lines (Fig. 34), and as they increase in width with the amount of aqueous vapour in the atmosphere, they are known as the *rain-band*, and are useful for measuring the humidity of the atmosphere and predicting weather. Similarly, the A and B Fraunhofer lines have been proved to be due to the absorptive action of atmospheric oxygen.

Wave-frequency as influenced by Motion—Doppler's Principle.—When a source of sound has a rapid motion towards or away from a listener, he hears the sound gradually changing in pitch. For example, when an express train rushes whistling through a railway station, persons hear the pitch of the whistle rising while the engine is approaching and falling after it has passed. Perhaps this will be best understood if we suppose the sounding body stationary, and the observer either approaching or receding from it. Then if he be approaching it, it is obvious that the number of waves meeting his ear per second will be greater than the actual frequency of the waves by the number of wave-lengths he passed over in a second, and if he be receding from it, the frequency will be diminished. Hence the pitch will be correspondingly affected, since it depends on the number of air-waves striking the ear in a second.

This illustrates a general law known as DOPPLER'S PRINCIPLE, which is that *when we are approaching, or are approached by, a body which is emitting regular vibrations, then the number of waves received by us in a second is increased, and the wave-lengths correspondingly diminished, and* vice versâ *when the distance of the vibrating body is increasing.* The original wave-length of the vibrations bears to the apparent change of the wave-length produced by the approach or recession the same ratio as the velocity of propagation bears to the apparent change in the velocity of propagation (*i.e.* the velocity of approach or recession); that is to say—

$$\text{Wave-length} : \left\{\begin{matrix}\text{difference of wave-}\\ \text{length produced}\end{matrix}\right\} :: \left\{\begin{matrix}\text{velocity of}\\ \text{propagation}\end{matrix}\right\} . \left\{\begin{matrix}\text{velocity of approach}\\ \text{or recession.}\end{matrix}\right.$$

The most important application of the above principle is to the case of light. When a luminous object is approaching us, its light is, as it were, sharpened in pitch—that is to say, its wave-lengths are diminished; and if it is receding, its wave-lengths are increased. But every particular wave-length has its own position in the spectrum, and the lines in the spectrum of a body approaching us are shifted a little towards the violet end, and if it is receding they are shifted towards the red end of the spectrum. By comparing the lines in the spectrum of a heavenly body with the same lines in a substance vaporized in the laboratory, we can tell the amount of shift of the lines, and hence the change of wave-length produced by the motion of the body. Suppose, for example, a spectral line whose normal wave-length is 0·000058 cm. is seen to be shifted in a star's spectrum to a position whose wave-length is 0·00005802 cm. Then the wave-length is increased 0·00000002 cm., and therefore the star is receding, and by the above proportion we have—

0·000058 : 0·00000002 : : 186330 miles per second : velocity of recession = about 64 miles per sec.

In this way, by the displacement of known lines in the spectrum, Doppler's principle has furnished a means of estimating the velocity of relative approach or recession of the earth and many stars, the rate of rotation of the sun about its axis, etc.

Spectrum Analysis is the study of the chemical composition and physical condition of luminous bodies by analyzing the light which they emit. The following are a few examples of the application of the method :—

1. *In chemical analysis.* The spectrum of an element which is in the state of an incandescent vapour consists of bright lines, and the lines of different elements differ in the positions which they hold in the spectrum. Hence an element can with certainty be detected by its characteristic spectrum, and a number of rare elements that had previously escaped detection have been discovered by the spectroscope.

In some cases compounds have a spectrum of their own, different from the spectra of the component elements, but in the majority of cases the molecules of the compound are broken up at the temperature necessary for incandescence.

2. *In determining the chemical composition and physical constitution of heavenly bodies.* By the bright lines in the spectrum of a celestial body we can tell the nature of the matter which caused the vibrations, and by the dark

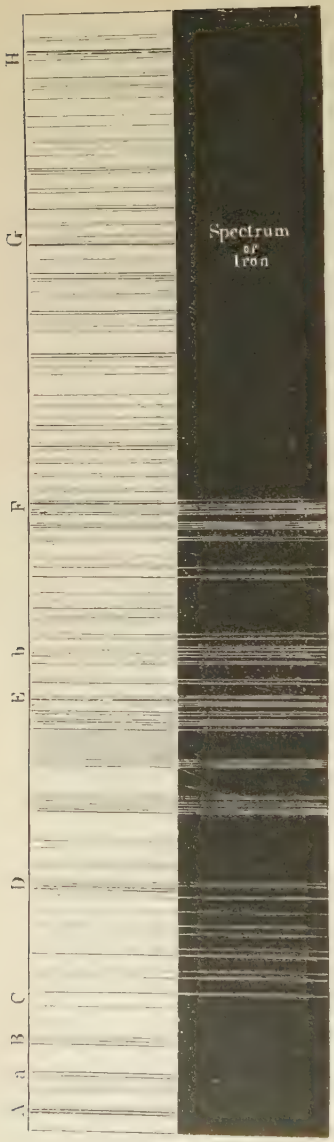


FIG. 38.—Correspondence of some of the lines given out by iron vapour, with some of the Fraunhofer lines in the solar spectrum.

absorption lines we can tell the nature of the gases in the atmosphere of the body. For example, by focusing sunlight on the upper half of the slit of a spectroscope, and the light of white-hot iron vapour on the lower half of the slit, we obtain the spectrum of the sun and the spectrum of iron vapour lying edge to edge, and by comparing the two we can tell which of the Fraunhofer lines are due to iron (see Fig. 38). In a similar way we can tell the other constituents of the sun's atmosphere.

3. *In measuring the velocity with which the earth and certain heavenly bodies are approaching or receding from one another.* We have described the method of doing this in the last section. The best way of determining the amount of shift of the lines is to photograph side by side the spectrum of the body and an element known to exist in it. In this way it has been found, for instance, that Sirius is approaching us at the rate of $15\frac{1}{2}$ miles a second, and Aldebaran receding at the rate of 30 miles a second. The famous nebula in Orion is retreating from our system at the rate of about 10 miles a second; and so on.

The spectroscopic method has also been successfully applied to determine the rate of rotation of the sun, and the velocity of solar winds, and of uprushes and downrushes of vapours in its atmosphere.

Questions.

1. Give a short account of the various radiation waves that pass along the ether.

2. How can it be proved that ether-waves exist which do not affect the sense of sight?

3. Show that at each end of the visible spectrum of white light there is a manifestation of radiant energy that does not affect the eye.

4. What is meant by the infra-red and the ultra-violet portions of a spectrum? How does photography aid us in investigating these regions?

5. Explain why we regard waves of radiant heat, of light, and of chemical energy as all of one kind. Show that some ether-waves manifest all three kinds of energy.

6. Describe the construction and mode of use of the spectroscope. State what you know about the spectrum of sodium, and of the sun.

7. What is the effect on a spectrum of (*a*) increasing the number of prisms, (*b*) increasing the width of the slit, (*c*) decreasing the width of the slit, (*d*) raising the temperature of a gas under examination, (*e*) increasing the pressure on a gas?

8. Give some account of the absorption of wave-motion.

9. Describe an experiment to illustrate the absorption of ether-waves.

10. How does heat pass from the sun to the earth? What effect has the earth's atmosphere on the rays of heat passing through it?

11. What part does the water-vapour, which is always present in the air, play in modifying the temperature of any locality?

12. In certain hot countries intense heat in the daytime is followed by frost at night: explain.

13. How do you explain the cold in the upper regions of the atmosphere when the sun is shining brightly?

14. When observing with an ordinary spectroscope, why do we get bright or dark lines, as the case may be, across the spectrum?

15. How do we account for the dark lines in the solar spectrum?

16. Describe the spectrum of sunlight, and state how the spectrum is affected when the sunlight passes through water-vapour.

17. What is the difference in the solar spectrum, the electric-arc spectrum, and the lightning spectrum?

18. Describe some of the uses of spectrum analysis.

19. Describe a spectroscope. How does it enable us to tell the composition of heavenly bodies?

20. As iron is gradually heated from blackness to a white heat what changes take place in its spectrum? (See Answers.)

CHAPTER VI.

THE ATMOSPHERE—OPTICAL PHENOMENA.

Dust and Other Fine Particles in the Atmosphere.—Dust is everywhere present in the atmosphere, even over the open ocean, and at the highest altitudes yet tested.

Origin of the Particles.—A large quantity of it must be of *meteoric origin*, for it is calculated that about 20 million meteors, visible to the naked eye, enter the earth's atmosphere per day, and if we include the telescopic meteors the number becomes about 400 millions a day. These are disintegrated by the friction of the air, and form the so-called "cosmic dust." Also there is the dust of *terrestrial origin* carried up into the atmosphere by ascending currents. This may be derived in innumerable ways, such as from the wearing away of rocks by the action of the atmosphere and of water, from volcanic eruptions, from the grinding and tear and wear of street traffic, from sea-spray in the form of fine particles of salt, from the pollen of flowers, from the crumbling to dust of the bark and leaves shed by trees, from the scales given off by the skin of men and animals, from the decomposition of all perishable materials, from burning fuel, from factories, and from minute organisms either plants or animals. Indeed, the origin of the solid particles in the atmosphere may be said to be universal.

Quantity of Dust in the Air.—Mr. John Aitken, F.R.S., the discoverer of the important part played by dust in the air, has invented a simple instrument called a koniscope (Gr. *konis*, "dust;" *skopeo*, "I inspect"), by which the number of dust-motes present in any sample of air can be counted.[1] It consists of a metal tube with glass ends. Near one end of the tube is an opening which is connected with an air-pump, and near the other end is a stop-cock for admitting the air to be tested. After the admission of the air the stop-cock is closed,

[1] *Transactions Royal Soc. Edin.*, vol. xxxv. p. 1 (1888); and *Proc. Royal Soc. Edin.*, vol. xvii. p. 246 (1890).

the tube pointed towards some suitable source of light, preferably daylight, so as to illuminate it from end to end, and one full stroke of the air-pump made. The air remaining in the tube is thus expanded and cooled, and a cloudy condensation of its moisture takes place, through which the light viewed assumes a certain tint depending on the number of dust-particles present in the air. For an instrument with a tube half a metre long, and an air-pump about three-fourths of the capacity of the tube, it is found that 80,000 particles of dust per cubic centimetre give a very faint colour, 1,500,000 a bright blue, while 4,000,000 give an extremely dark blue.

Mr. Aitken has tested the number of dust-particles in the atmosphere at many places in Great Britain and on the Continent, and, showing how greatly the atmosphere is polluted with dust produced by human agency, he found that while there may be hundreds of particles per cubic centimetre of air in remote country districts, near villages the number goes up to thousands, and in cities to hundreds of thousands. For instance, in the moors of Argyllshire in Scotland, and on the top of the Rigi in Switzerland, he counted 200 motes per cubic centimetre, and in Edinburgh, near Waverley Station, he found on one occasion 3 millions per cubic centimetre.

Action of Dust and Fine Particles in the Atmosphere.

1. *The dust-particles act as nuclei on which condensation may take place, even though the air itself may not be saturated.* Mr. Aitken proved this by connecting two large glass receivers, A and B, with a small boiler. Both receivers were filled with ordinary air from the room, but as the air entered B it had to pass through a filter of cotton-wool, so that all dust was removed from it. Steam from the boiler was led into both A and B, and at once in A a cloud of condensed vapour formed which became so dense that an observer could not see through it, while the air in B remained perfectly transparent although super-saturated. Thus no condensation of water-vapour can occur without nuclei; that is, without dust-particles in the air there could be no fog, mist, cloud, nor rain. If the particles be numerous, each one's share of the condensed moisture is small, and a fog is the result; whereas if they be few, each gets more, and mist, cloud, or rain is produced. It is to the presence of immense numbers of these nuclei that the dense dry black fogs of large towns are due.

2. *The dust-particles are good absorbers, and therefore good*

radiators of heat. Being good radiators, they help to produce fogs in another way besides acting as nuclei, for they increase the radiating power of the air so that it cools quickly and its vapour is condensed on the dust-particles, thus producing a fog.

Again, being good absorbers of heat, the dust-particles absorb the heat radiated by the earth, and so prevent it passing into space by night. On p. 70 we spoke of the athermancy of the water-vapour in the air to the dark heat radiated from the earth, so that the water-vapour in the atmosphere acts as a blanket round the earth by night. But Mr. Aitken's investigations seem to show that the entrapping of the earth's heat is not due so much to the invisible water-vapour in the air, as to the dust-motes and condensed water-particles in the air.

3. *Haze is principally produced by dust.* It is generally seen in dry air, and is due to the numerous dust-particles condensing the moisture at a temperature above the dew-point.

4. **Atmospheric Reflection.**

(*a*) *The Scattering and Diffusion of Light.*—If there were no dust-particles in the atmosphere to scatter the sun's light, then his rays would come to us in straight lines, leaving all surrounding space dark except where a bright spot marked the position of a star or planet. In short, the sky by day would differ from that by night only by the presence of the sun. When exposed to his rays, we would be in dazzling light, and when in shadow, in impenetrable darkness. But the myriads of floating dust-motes and other particles catch the sun's rays, and scatter them in all directions by reflection, thus toning down the abrupt changes from direct sunlight to shade, diffusing the light and illuminating the whole atmosphere so that not even the brightest stars are visible by day.

(*b*) *The Blue Colour of the Sky.*—Some of the rays of the sun that strike the higher regions of the atmosphere are reflected back to us by the dust-motes there. The blue rays, being those due to the shortest waves and waves of greatest frequency in the ether, are most easily turned back or reflected; whereas the longer waves of lower frequency—the red and yellow—are not so much interfered with, and are mostly able to pass on. Hence the unclouded sky seems blue because its particles reflect back to us chiefly the blue rays reaching them from the sun.

(*c*) *The Red Tints at Sunrise and Sunset.*—We have said that the dust-motes allow the long red rays mostly to pass on, while

they intercept and reflect the short bluish ones. Now, when the sun is near the horizon we see it through a great thickness of the lower atmosphere, which contains the largest number of motes; consequently, most of the blue rays are reflected in other directions away from us, whereas the rays that pass through to us are mostly red, and hence the sun near the horizon seems reddish.

Expt. 32.—The action of fine particles in producing the phenomena of (*b*) and (*c*) may be experimentally illustrated as follows: Take a narrow flat trough with glass sides, and having filled it with water, insert it in the stage of an optical lantern, and observe the round white disc upon the screen. Introduce a few drops of milk and stir the liquid so as to distribute the particles of milk uniformly through it, and observe that the disc is now yellow or red. Now remove the trough and place a dark background behind it, and observe that the milky fluid has a bluish tinge when seen by reflected light.

The experiment could be repeated by dissolving some resin or mastic by alcohol and introducing a few drops of the solution into the trough.

It is for a similar reason that our atmosphere seems blue when seen by the light reflected from its countless dust and water particles, whereas the light it transmits is always more or less yellow or red, as is seen when the sun shines through a fog or a great thickness of the atmosphere when our luminary is low in the sky.

(*d*) *The soft shimmering light called twilight* (half light) is produced by the dust and other particles in the upper atmosphere reflecting the rays of the sun when it is below the

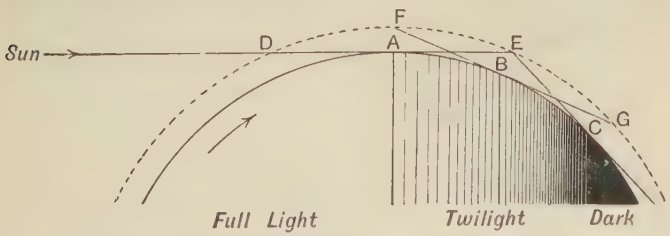


Fig. 39.—To explain twilight. The dotted curve represents the highest limit of the atmosphere reflecting the sun's rays. (After *Hinman.*)

horizon after sunset or before sunrise. Morning twilight is generally called dawn.

Suppose the sun is just setting in the west at the place A (Fig. 39), then A will be illuminated by the last of the sun's direct beams, and also by the rays reflected from the portion

from D to E of the atmosphere above the horizon at the time. When the rotation of the earth has carried A to B, the sun will be below the horizon FG, but still B is not in total darkness, because light reflected from every point of the sky between F and E illumines it with twilight. When A has been carried to C, so that the horizon is EC, then neither direct nor reflected light from the sun reaches it, and it is therefore in darkness.

Twilight ceases at any place when the sun is 18° vertically below the horizon, and the time taken by the sun to reach this limit is different in different latitudes, and it varies also for the same latitude with the time of the year. It varies with latitude, because the angle at which the sun rises and sets to the horizon is the complement of the latitude. Hence at the equator, latitude 0°, the sun sets perpendicularly to the horizon, and therefore soon descends 18° below it. Indeed, since the earth rotates 15° per hour, twilight and dawn each last about 1¼ hour at the equator. As latitude increases the sun sets in a more and more slanting direction to the horizon, and therefore takes a longer time to get 18° vertically below it. In our latitude twilight and dawn each last on an average about 2½ hours, while at the pole they are each about two months long, for it takes the sun this time to descend or ascend the 18°.

Again, the duration of twilight at any place depends upon the seasons, being shortest at the equinoxes and longest at the solstices. In Fig. 39, the width of the twilight zone ABC is about 18°, and at the equinox the sun is over the equator and by the rotation of the earth crosses the zone perpendicularly, whereas at the solstices the sun crosses this zone in a slanting direction and of course requires longer to do so.

Atmospheric Refraction.—The lower parts of the atmosphere have to support the weight of all the parts above them; hence, since air is compressible, the atmosphere becomes denser and denser towards the earth's surface, as is roughly indicated by the distances between the dotted curves in Fig. 40.

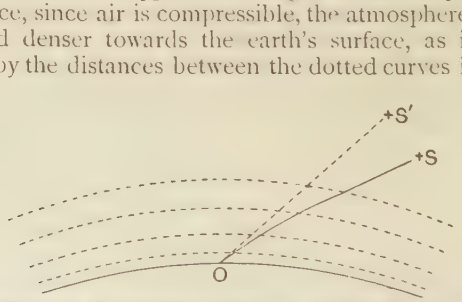


Fig. 40.– Atmospheric refraction increases the apparent altitude of heavenly bodies.

Hence a ray from a star is subjected to a succession of small deviations towards the normal as it passes into the denser and denser parts of our atmosphere, so that the ray traverses it in a curved path with the concave side towards the earth. But an

object is seen in the direction in which the rays from it enter the eye, so that if O be the position of an observer, the star will seem at S′, in the direction of the tangent at O to the curve.

1. *The amount of atmospheric refraction* for a heavenly body depends on—

(*a*) *Its altitude.* A body in the zenith is seen in its true direction, but in descending from the zenith to the horizon the refraction continually increases. As will be seen from Fig. 41, the amount of refraction increases very rapidly near the horizon because of the rapid increase in the density of the atmosphere there, and also because the rays have to pass through a great thickness of the atmosphere.

(*b*) *The atmospheric pressure.* Refraction is greater than the mean when the barometer is high, and *vice versâ*.

(*c*) *The temperature of the atmosphere.* The colder the air the denser it is, and the greater is its refractive power.

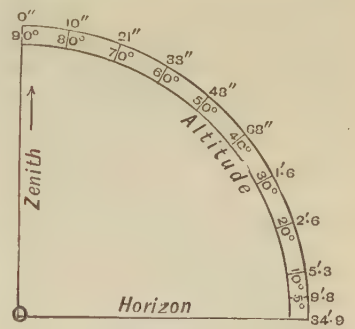


Fig. 41.—Mean refraction at different altitudes. The numbers outside the curve give the amount of refraction for heavenly bodies at the stated altitudes.

In astronomical observations, it is necessary to make a correction for refraction in order to get the true direction of a heavenly body from its apparent direction, and elaborate *Refraction Tables*, giving the value of refraction for every altitude of a star and for different temperatures and pressures of the air, have been constructed for the use of astronomers. Of course, the true altitude of a heavenly body is its apparent altitude *minus* this correction.

2. *Some of the effects of atmospheric refraction.*

(*a*) We do not see heavenly bodies in their true direction unless they be in the zenith. They all appear higher above the horizon than they really are.

(*b*) It lengthens the period of daylight. The amount of atmospheric refraction at the horizon is nearly 35′, and the angular diameter of the sun is about 32′, hence in the evening and morning it appears to be a little above the horizon when, were there no atmosphere, it would be just below it. This lengthens the period of sunlight altogether by about 4 minutes at the equator. In our latitude refraction causes us to see the sun 5 minutes after it sets and 5 minutes before it rises, and so

daylight is lengthened 10 minutes. At the poles the day of 6 months is lengthened 3 days by refraction.

(*c*) In the same way terrestrial objects really below the horizon may by refraction seem above it, and so objects at great distances may become visible. For example, Snowdon is now and then visible to pilots in Dublin Bay; the Isle of Wight has several times been seen from Brighton; and from the same place the coast of France as far as Dieppe has been seen.

(*d*) The sun or moon near the horizon seems oval-shaped. The whole disc is raised by refraction, but the refraction is greatest for the lower part of the disc because the rays from it pass through the greatest thickness of atmosphere. In this way the vertical diameter appears contracted, the lower edge of the disc appearing more flattened than the upper. This effect is more pronounced in winter than in summer.

The sun or moon *seems* larger when low down than when high up in the sky. This is an optical illusion, for when the angular diameter is measured instrumentally it is found to be the same whether the body is at its greatest altitude or near the horizon. The explanation of the illusion is that when the sun and moon are low in the sky, the eye estimates their sizes by comparison with terrestrial objects nearly in the same line (trees, houses, etc.); but when the luminaries are at a considerable altitude no such comparison is possible, and a different estimate of their size is instinctively formed.

(*e*) The twinkling or scintillation of fixed stars is due to the unequal refraction of rays from them as the rays pass through strata of the atmosphere of different temperatures and densities.

The Rainbow is a brilliant arch of light seen when the observer is in full sunshine while rain is falling from the opposite part of the sky to that in which the sun is shining. It is hardly necessary to describe the appearance of the bow minutely. It consists of a series of concentric circular bands exhibiting the colours of the spectrum in their well-known order, the red being highest or at the top of the bow, and the violet lowest or innermost, while between these there occur in succession the colours orange, yellow, green, and blue.

A rainbow is caused by the refraction and reflection of the sun's light by the raindrops. When a beam of sunlight, SA (Fig. 42), falls on a spherical drop, the latter acts like a prism and refracts the beam towards the perpendicular at the point of incidence, and at the same time decomposes the beam into its constituent colours, of which only the red and violet are indicated in the diagram. Part of this light is reflected at P,

the back of the drop, and emerges at the front of the drop again, where it undergoes a second refraction.

Why a Rainbow is circular, with red outermost and violet innermost.—It is found that all the violet rays emerging from drops always make an angle of about 40° with the incident ray, and the red rays an angle of about 42°. Hence, if SES′ (Fig. 42) be drawn parallel to SA, then the violet ray from each drop makes an angle of 40° with SES′, and the red ray an angle of 42°. Now, if E represent the position of the eye of an observer, and SES′ the direction of the sun's rays, then if we imagine all the violet rays from the infinite number of raindrops P_1, P_2, P_3, etc. (Fig. 43) drawn, each making an angle of 40° with SES′, they will

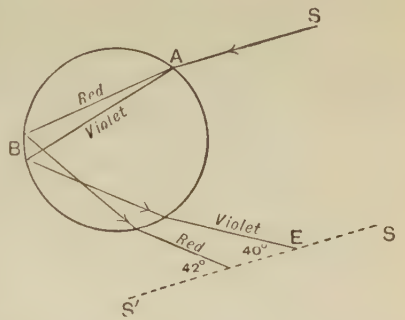


Fig. 42.—To explain the action of a raindrop on a ray of sunlight.

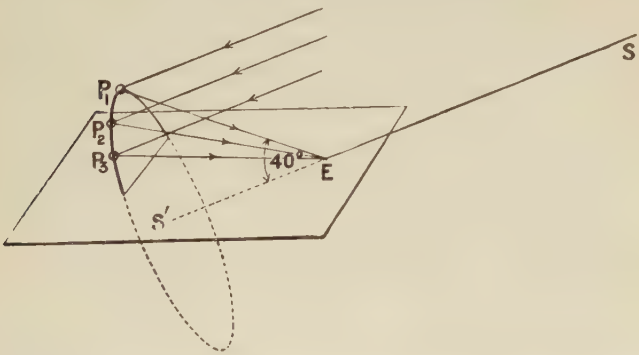


Fig. 43.—To explain why a rainbow is circular. (From Watson's *Text-Book of Physics.*)

form a cone having ES′ for axis, and where this cone of violet rays meets the rain-cloud there will be seen a violet-coloured circle with its centre in the line ES′, and having a radius subtending at E an angle of 40°. Similarly, there will be a cone

of red rays having its apex at E, and consisting of all the rays forming an angle of 42° with ES', so that there will also be seen in the opposite part of the sky from the sun a circle of red rays having a radius subtending at E an angle of 42° and its centre at the same point in the line ES' as the violet circle. Between these two cones will lie the cones of the colours intermediate in wave-length. Hence the red circle is outermost, and the violet innermost, and between them come circles of the other colours constituting the rainbow.

No two persons see exactly the same rainbow, for they cannot simultaneously have an eye at E.

The amount of the circular arch visible at any time depends on the altitude of the sun. Since the centre of the sun, the spectator's eye, and the centre of the bow all lie in the same straight line SES', we can never on the surface of the earth (represented by the four-sided figure in the diagram) see more than half the circle of the rainbow, and this will be when the sun is on the horizon. As the sun rises in the sky the centre S' of the rainbow descends below the horizon, and consequently less and less of the circle is seen. When the sun is at an altitude of 42°, the top of the red arch will just touch the horizon; and for greater altitudes of the sun the bow is entirely below the horizon, and therefore invisible.

As a person ascends above the earth's surface he sees more than half the bow, and by ascending a sufficiently high mountain the entire circle may be seen.

Atmospheric Electricity.—The atmosphere is always more or less electrified, generally with positive electricity in fine weather. The quantity of electricity in the atmosphere increases with altitude. The clouds are always more or less charged, sometimes with positive electricity, and sometimes with negative.

The Causes of Atmospheric Electricity are not very well known:—

1. *Evaporation is probably the chief source of atmospheric electricity.*

Expt. 33.—Put some salt water into the lid of a tin canister, and place the lid on the top of a gold-leaf electroscope, and into the water drop a hot cinder, and observe the behaviour of the leaves. Instead of the salt water, a solution of sulphate of copper may be used; indeed, in order that the experiment may be successful, it is necessary to use not pure water, but water containing some foreign matter.

The leaves diverge with negative electricity, and the vapour,

if tested, would be found to be positively charged. Great evaporation takes place over the surface of the sea, and the vapour produced must carry up into the atmosphere a large amount of electricity. No water in nature is perfectly pure, so that the vapour rising from all water surfaces is to some extent electrified. It is because atmospheric electricity is chiefly due to evaporation that thunderstorms occur most frequently in the tropics, and usually during the daytime, and that in any latitude they are more common in summer than in winter.

2. *Atmospheric electricity is partly the result of friction.*

EXPT. 34.—By means of bellows, blow a current of air against the cap of a gold-leaf electroscope, and observe the leaves.

The friction of winds over the earth must produce electricity, and so must the friction between currents of air at different temperatures.

Volcanic eruptions are frequently accompanied by brilliant flashes of lightning, and it is believed that the electricity is chiefly produced by the friction of the vapours and other ejecta against the sides of the orifice through which they escape. But it may also in this case be partly due to the uprushing water-vapour becoming cooled and condensed in the elevated region, and forming a cloud which, being a conductor of electricity, collects the electricity previously existing in the air and discharges it upon the summit of the volcano.

Atmospheric electricity reveals itself from time to time by certain phenomena the chief of which are thunder and lightning, and the aurora.

Lightning.

Identity between Lightning and the Electric Spark.—Benjamin Franklin, 150 years ago, proved the identity of the electricity of a thunder-cloud with that obtainable from an electrical machine, by sending up a kite and attaching to the lower end of the string a key to act as a discharger, and to the key a silk ribbon to prevent the discharge passing through his body. As soon as the rain wetted the string, and so made it a good conductor of electricity, he found that sparks could be obtained from the key similar to those from an electrical machine, and that he could charge a Leyden jar from the clouds.

If the positive and negative poles of an electrical machine be brought near each other, the opposite kinds of electricity attract one another, and are only prevented from combining by the bad conductor, the air, between them. But by continued

working of the machine the charges of electricity increase, and ultimately attract each other so strongly that they combine in spite of the air, which, however, is made white-hot because of the resistance it offers to the passage of the electricity through it. Lightning is nothing more than a great electric spark, often more than a mile, and sometimes five or even ten miles in length.

Cause of Lightning.—Millions of particles of water-vapour condense to form each particle of water in a cloud, and the water-particles unite to form raindrops. Hence, however small the amount of electricity possessed by each vapour-particle, the accumulation of it in a cloud-mass must be enormous. Moreover, electricity resides on the surface of a body, and the surface of a raindrop is smaller than the total surfaces of the water-particles which combine to form it. Hence, however small may be the intensity of the electricity produced in the vapour-particles by the evaporation, its intensity in the cloud-particles formed by their condensation will be much greater, and it will be still further increased by the coalescence of the latter to form raindrops. In this way the intensity of the electricity in a cloud may become so great that the electricity of the cloud and the opposite kind induced by it in a neighbouring cloud or the earth rush together through the intervening air. The electrical energy is then mainly converted into heat by the resistance of the air, the particles of which become white-hot, and so rapid is the passage of the electricity that the duration of the brilliant flash may be only about one-millionth part of a second.

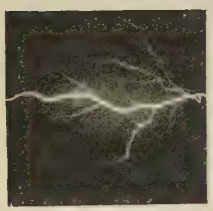
Before the flash occurred, the drops in the cloud were repelling each other because of their being similarly electrified; hence after the flash they more readily coalesce to form larger drops, and this may be the reason that a downpour of rain generally quickly follows a flash of lightning.

Varieties of Lightning.—There are generally said to be three kinds of lightning-flashes, known respectively as forked lightning, sheet lightning, and ball lightning.

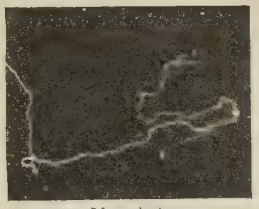
1. *So-called Forked Lightning.* A thunderstorm Committee of the Royal Meteorological Society, in 1888, issued a Report based on a large number of photographs of lightning-flashes in various parts of Europe and America. The photographs show that the traditional forked or zigzag lightning-flashes of artists have no existence in nature, and that lightning of this kind assumes the following typical forms :—

(*a*) *Stream lightning*, a plain, broad, rather smooth streak of light without distinct irregularities or branches.

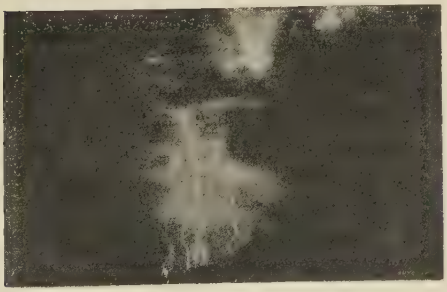
Stream.



Ramified.



Meandering.



Sinuous.

FIG. 44.—Photographs showing varieties of so-called forked lightning. (From *Quarterly Journal of Royal Meteorological Society*, vol. xiv., 1888. By permission.)

(*b*) *Sinuous lightning*, in which the flash keeps in one general direction although the path is wavering or sinuous, *i.e.* bending from one side to the other in a very irregular manner. The irregularity of the path is due to the different densities and resistances of different portions of the air. The lowermost photograph in Fig. 44 shows several sinuous flashes. This is by far

the commonest type, and bears a close resemblance to the sparks of an electrical machine.

(*c*) *Ramified lightning*, in which parts of the flash appear to branch off from the main streak.

(*d*) *Meandering lightning*, in which the flash meanders about without a definite course, forming small irregular loops which are the effect of perspective; the flash does not really cross its former track, for different parts of the track are at different distances from the observer.

(*e*) *Beaded lightning*. Sometimes a number of bright beads of light appear in lightning photographs, especially at the bends in the meandering type (see Fig. 44). These are probably points at which the flash was either moving directly towards or away from the observer, thereby giving a longer exposure of those parts to the photographic plate.

(*f*) *Ribbon lightning*, in which the flash assumes a more or less ribbon-like form. It is not certain whether this is a distinct type, or whether it is due to a shaking of the camera during the flash.

2. *Sheet Lightning* is a broad sheet of pale diffused light. It is harmless, and is usually the reflection in the atmosphere of lightning too distant for the thunder to be audible. Sometimes it may be a weak discharge within a cloud at an altitude at which the air is rare.

3. *Ball or Globular Lightning* is a very rare form which has not yet been satisfactorily explained. It appears as a ball of fire varying in diameter from a few inches to two or three feet, moving slowly and remaining visible for several seconds or even minutes, and generally bursting at last with a loud report.

Of course no material substance falls to the earth during a thunderstorm. There is no such thing as a thunderbolt.

Thunder is the noise which accompanies a flash of lightning, and it has the same cause as the crackle which accompanies the sparks from an electrical machine. The air along the track of the lightning is suddenly heated and rarefied, and it as suddenly and violently contracts again when the heating has ceased with the passage of the flash. Then it rebounds, and so on, and in this way a succession of air-waves reaches the ear.

Interval between Flash and Report—Distance of Thunder-cloud.—There is usually an interval of a few seconds between lightning and the accompanying thunder, because the transmission of light is nearly instantaneous, whereas that of sound is only at the rate of 1100 feet per second. Thus an interval of 5 seconds would show that the flash occurred about a mile away from the observer. The greatest interval recorded is 72 seconds, indicating a distance of 15 miles, and apart from this exceptional case thunder has not been heard at a greater

distance than 10 miles; and these facts are remarkable, as the report of a cannon has been heard more than 60 miles off.[1]

Duration of Thunder.—When the flash is short, and passes near to the observer, a sudden crash is heard, sometimes called a *thunderclap*. The pealing or rolling of thunder may be due to different causes. If the flash is a long one, and parts of it are at unequal distances from the observer, then the peal will be prolonged owing to sounds from portions farther and farther from him arriving one after the other. And if the path of the lightning be very irregular, then stretches of it may be at the same distance from the listener, and the sounds from all parts of those stretches will reach him simultaneously, and so the prolonged peal may not be of uniform loudness. But the rolling of thunder is due in great measure to the prolongation of the sound by echoes from clouds or from the earth's surface and hills.

The destructive effects of lightning may be said to be mechanical, combustible, and physiological. An electrified cloud induces the opposite kind of electricity in the earth beneath it, and the attraction between the two may become so great that a discharge occurs between cloud and earth, the discharge taking place most commonly through elevated objects, such as hills, trees, high buildings, etc. In this way houses may be set on fire, and masses of masonry, like towers and chimney-stacks, thrown down. Trees are often struck, as the sap of trees makes them better conductors than the air, and an electric discharge always follows the path of least resistance. The sudden volatilization and expansion of the sap may rend the tree in pieces, or it may tear off the bark and branches, and plough long furrows in the wood as if the tree had been struck with tremendous force by a sharp instrument. It is very dangerous to take shelter from the storm under a tree, as the animal or human body is a better conductor than wood, and therefore the discharge may leave the tree and pass through the body, producing a violent excitement of the nerve centres or muscular tissues, causing death, frequently without any external injury.

By what is called the *return shock*, severe physiological effects may be produced without the actual passage of the electric discharge through the body. The inductive action

[1] The firing of the guns by the fleet in the Solent during the funeral of Queen Victoria was heard at Oxford and Eastbourne (65 miles off), and at other places even more distant.

of an electrified cloud overhead separates the two kinds of electricity in the body of a person beneath it, attracting the unlike and repelling the like kind away as far as possible into the earth. Then when the flash takes place this inductive action ceases, the repelled like kind of electricity returns into the body, and the intensified unlike kind passes out of the body so suddenly as to cause a severe shock which may knock the person down insensible, but is seldom fatal.

The Aurora.—The *aurora borealis*, or northern light, is a beautiful luminous appearance often seen at night in high northern latitudes. A similar phenomenon in the southern

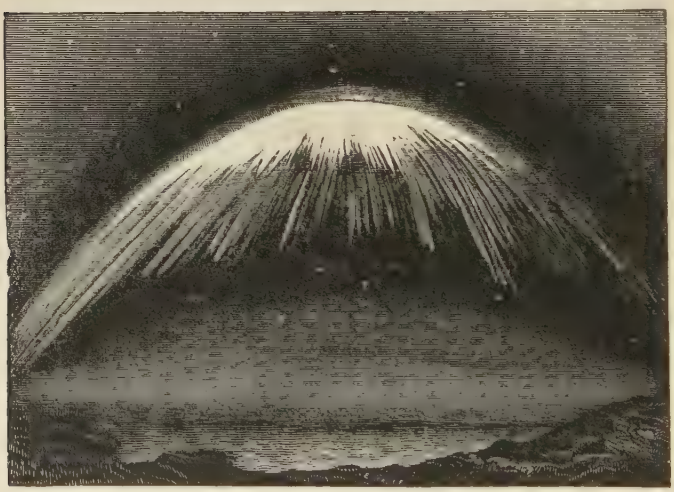


FIG. 45.—The aurora borealis. (From Ganot's *Natural Philosophy*.)

hemisphere is called the *aurora australis*, or southern light. A general term often applied to the auroræ of both hemispheres is the *aurora polaris*, or polar light.

Appearance.—Auroræ exhibit an almost infinite variety of appearances, so that no general description can be given to include them all. In our island the aurora is most frequent in spring and autumn, and usually commences as a low arch of white or pale greenish-yellow light stretching across the north-western horizon. Beneath this arch the sky appears darker than the rest of the heavens; this is sometimes called the

"dark segment" of the aurora. Occasionally there are several arches, as many as nine having been counted at one time. From the luminous arch there generally rise numerous streamers or jets of light, which shoot upwards with a pulsing, tremulous appearance described by Burns in the well-known lines—

"Like the Borealis race
That flits ere you can point the place."

The streamers are always parallel to the direction of a dipping-needle, so that, owing to perspective, they all seem directed towards the region of the heavens to which the axis of a dipping-needle points. Although the aurora is usually white or greenish-yellow, sometimes deep red, crimson, violet, steel-blue, and other colours flash out, giving a gorgeous aspect to the whole display. Incessant movement characterizes the aurora. Along the arch brilliant wave-like flashes pass from one end to the other, giving the appearance of flapping like a flag in a breeze. The streamers lengthen and shorten with a dart-like motion towards their point of concourse, and sometimes they are so elongated as to appear to meet round this spot and form a luminous ring, called the crown or corona of the aurora.

Height.—The height at which auroral discharges take place is still uncertain, owing to the difficulty in obtaining reliable data as to the direction in which the same features in the auroral arch are seen simultaneously from a large number of different standpoints. It seldom appears at a less elevation than 45 miles; its average height is probably about 75 miles, but, according to Loomis, streamers frequently extend upwards to an elevation of 500 miles.

Distribution in latitude.—The aurora is rarely seen close to the equator or in low latitudes generally. The region in the northern hemisphere where it is most common is not at the north pole, but in an oval-shaped belt which surrounds it. In Russia and Siberia this zone extends from the arctic circle to 75° N. lat. In America it is broader, extending as far south as lat. 50°.

Cause of the Phenomenon.—It is now generally agreed that the glow of the aurora is mainly due to electric discharges through the rare air in the higher regions of the atmosphere, as it closely resembles the glow seen when an electric discharge is sent through a glass tube containing highly rarefied

air. And just as the colour of the glow in such a "vacuum" tube depends on the tenuity of the air in it, so the variations of colour in the aurora may be due to the altitude, and therefore density, of the air in which the discharge takes place. In his presidential address to the Royal Meteorological Society in 1888 Dr. Marcet said, "The aurora borealis is now generally considered as due to positive electricity from the sea between the tropics being carried into the upper atmospheric regions, and thence wafted to the poles by the higher currents of air. Here it descends towards the earth, and meets the terrestrial negative electricity in a rarefied atmosphere." Electric discharges therefore take place, rendering the air incandescent. Sir Norman Lockyer believes that a considerable part of the luminosity is due to the electric discharges heating and vaporizing some of the meteoritic particles which occur in the atmosphere in enormous numbers.

Questions.

1. Of what does atmospheric dust consist? What effects do the dust-particles produce in the atmosphere?
2. Explain the cause of the blue colour of the sky above our heads, and of the red glow in the lower parts of the sky at sunset.
3. Distinguish between the effects of selective diffusion and selective absorption produced by the earth's atmosphere.
4. What effect has refraction on the apparent position of a star? Show that the greater the altitude of the star the less it is displaced by refraction, and that a star in the zenith is not displaced at all.
5. Explain why we are able to see the sun after it has sunk below the horizon.
6. If the earth had no atmosphere, how would the duration of daylight differ from what it is at present?
7. What would be the effect of refraction on terrestrial objects as seen by a fish under water?
8. How are the colours produced in the rainbow? What is the greatest amount of a rainbow that can be seen by a person at sea-level, and why? Why cannot two persons see the same rainbow?
9. Specify the various forms into which lightning-flashes may be classified.
10. Give an account of recent researches in connection with the nature of lightning-flashes, especially as illustrated by photography.
11. Explain the origin of the dark clouds which prevail during thunderstorms.
12. What is the aurora? What is lightning? How do you suppose these phenomena are produced?
13. Where are the phenomena known as aurorae best seen? What causes are generally supposed to explain their occurrence?
14. State what you know concerning the spectra of lightning and the aurora.

CHAPTER VII.

ATMOSPHERIC PHENOMENA IN RELATION TO CLIMATE.

We must take for granted that the student has an elementary knowledge of the composition, temperature, and pressure of the atmosphere; winds and their causes; evaporation, and the chief forms that the water-vapour in the atmosphere takes when condensed, viz. dew, hoar-frost, fog, mist, clouds, rain, snow, hail (see *Elementary Physiography*, chapters xiii., xiv., and xv.).

Relative Humidity of the Atmosphere.—There is always water-vapour in the atmosphere, and the mass of it present in a unit volume of air is called the *absolute humidity* of the air. But this gives us little information as to the dampness or dryness of the air, which depends, not on the actual amount of vapour in the air, but on the nearness of the air to saturation, or, to express it more definitely, on *the ratio of the mass of water-vapour present in the air to the mass that would saturate it at the same temperature.* This ratio is called the *relative humidity* of the air, or its *hygrometric state* or *fraction of saturation.*

Let T° be the temperature of the atmosphere, then—

$$\left.\begin{matrix}\text{Relative}\\ \text{humidity}\end{matrix}\right\} = \frac{\text{mass of water-vapour actually present in unit vol. of air at T°}}{\text{mass of water-vapour that would saturate unit vol. of air at T°}}$$

If the air were cooled down, it would eventually reach a temperature at which the vapour actually present in it would saturate it, and if cooled further, condensation of some of the vapour would take place as a cloud or as dew. This temperature is therefore known as the *dew-point.* Suppose it to be $t°$, then—

$$\left.\begin{matrix}\text{Relative}\\ \text{humidity}\end{matrix}\right\} = \frac{\text{mass of water-vapour that would saturate unit vol. of air at } t°}{\text{mass of water-vapour that would saturate unit vol. of air at T°}}$$

But, since equal volumes are taken, the ratio of the masses is the same as that of the densities, and therefore the same as

that of the pressures (for, by Boyle's law, the density of a gas is proportional to the pressure, and this is true for saturated air within small limits of error), therefore—

$$\text{Relative humidity} = \frac{\text{saturation pressure exerted by water-vapour at } t^\circ}{\text{saturation pressure exerted by water-vapour at } T^\circ}$$

The pressure exerted by the quantity of water-vapour that will saturate air is given for different temperatures in tables. The following are a few figures taken from such a table :—

PRESSURE OF SATURATED WATER-VAPOUR IN INCHES OF MERCURY.

Temperature.	Pressure.
50° F.	0·36
53°	0·40
57°	0·47
60°	0·52

For instance, suppose the temperature of the air to be 57° F. and the dew-point 50° F., then—

$$\text{Relative humidity of atmosphere} = \frac{0{\cdot}36}{0{\cdot}47} = 0{\cdot}77 \text{ nearly.}$$

It is usual to express the humidity as a percentage, so that the humidity would be $0{\cdot}77 \times 100 = 77$; that is to say, the atmosphere has only 77 per cent. of the water-vapour it could contain at that temperature.

A relative humidity of about 65 per cent. is pleasant and wholesome. Upon an average the air in this country has a humidity of about 75 per cent. The absolute humidity is greatest at sea-level, and diminishes rapidly as we ascend, for it has been calculated that one-half of the water-vapour in the atmosphere is contained in the lowest 6000 feet. The relative humidity, on the other hand, increases slightly up to about 3000 feet, where the atmosphere is saturated, and then gradually decreases. The vapour in the atmosphere checks the access of heat to the earth from the sun, and also the radiation of heat from the earth into space—hence the burning power of the sun's rays in the dry air on mountain-peaks.

It has been calculated that more than 20 per cent. of the heat of a sunbeam passing vertically through the atmosphere is lost, whereas hardly any of the heat of a nearly horizontal beam reaches the earth. It is for this reason that the rays of the sun are hotter at noon than in the morning or evening, when they have to pass through a much greater thickness of the moist and dense lower strata of the air.

Hygrometry (Gr. *hygros*, "moist;" *metron*, "a measure") is the measurement of the relative humidity of the atmosphere, and it is evident, from what has been said above, that for this

purpose we require to know the dew-point, the actual temperature, and to have a table of pressures of saturated water-vapour. There are several different classes of instruments for determining the dew-point, but we shall only refer to two, namely, condensation or dew-point hygrometers, and the dry-and-wet-bulb hygrometer. All the dew-point hygrometers utilize the same principle—a bright surface exposed to the air is gradually cooled, and thus the air in contact with it is cooled until the air becomes saturated and a film of moisture is deposited on the bright surface; the temperature at which this occurs is noted, and it is the dew-point required.

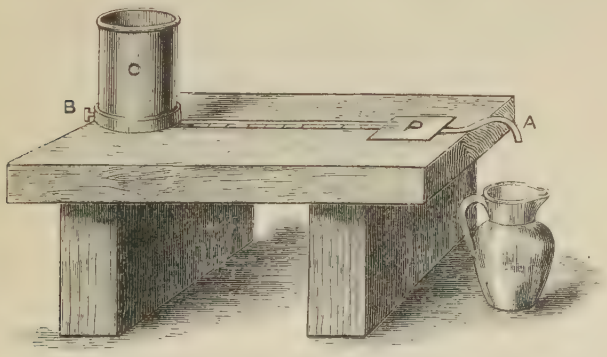


FIG. 46.—Dines's hygrometer.

Dines's hygrometer is one of the best modern dew-point hygrometers. In a vessel, C (Figs. 46 and 47), is placed water

FIG. 47.—Same shown in section. (From Wright's *Advanced Heat.*)

containing, if necessary, pieces of ice to cool it sufficiently. On opening a tap, B, the water flows along the pipe D into a chamber, R, and then out through the waste-pipe A. The

chamber is closed on the top by a very thin piece of blackened glass, P, just under which is the bulb of a delicate thermometer, T. A horizontal partition runs almost completely across the chamber and, by compelling the water to flow as indicated in Fig. 48, brings it into contact with the glass top and the thermometer bulb. The graduated stem of the thermometer is visible through a narrow groove in the stand (Fig. 46). The cold water chills the glass plate, and when the first trace of dew appears on the plate, the thermometer is read and the tap closed. As the cooling will very probably have been carried too far, this temperature will be lower than the dew-point, and hence the

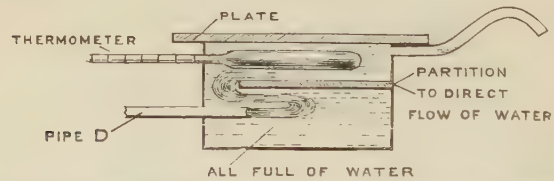


FIG. 48.—To show how the cold water in the chamber is brought into intimate contact with the blackened glass and the thermometer bulb. (From Wright's *Advanced Heat*.)

thermometer is again read at the moment when the last trace of dew disappears. This temperature will be a little higher than the dew-point (why?), but the mean of the two readings may be taken as the dew-point.

The experiment should be so arranged that the water in C is not much below the dew-point; indeed, in order to get good results with any form of dew-point hygrometer, the temperatures of the appearance and disappearance of the moisture should almost agree.

Suppose that the dew-point is found to be 53° F., and the temperature of the air 60° F., then, as explained in the last paragraph—

$$\text{The relative humidity of the atmosphere} = \frac{0{\cdot}40}{0{\cdot}52} = 0{\cdot}77, \text{or } 77\,\%.$$

The Wet-and-Dry-bulb Hygrometer.

EXPT. 35.—Note the reading of a thermometer standing in water at the temperature of the room; take the thermometer out of the water, and note the temporary effect of the evaporation on the reading.

Repeat the experiment, but while the thermometer is drying in the air, move it quickly backwards and forwards. What do you conclude as to the

connection between the rate of evaporation and the amount of cooling produced?

Expt. 36.—Moisten a thermometer bulb with methylated spirit (which rapidly evaporates), and compare the amount of cooling with the previous result. Also repeat the experiment, but move the thermometer quickly to and fro while drying.

The wet-and-dry-bulb hygrometer depends on the principle that evaporation causes cooling, and that the amount by which the temperature is lowered is greater the greater the rate of evaporation. The instrument consists of two ordinary thermometers fixed side by side on a frame. The bulb of one is covered with muslin kept moist by means of a piece of lamp-wick which dips into a small vessel containing distilled water. The water ascends the wick by capillary attraction, the wick having been previously boiled in ether to thoroughly free it from grease. The evaporation of the moisture in the muslin lowers the temperature of the wet bulb. The difference between the readings of the two thermometers is a measure of the dryness or humidity of the air, for if the air be very dry there will be rapid evaporation, and therefore great cooling, and the reading of the wet-bulb thermometer will be considerably lower than the dry. If the air be saturated there will be no evaporation, and the readings will be the same.

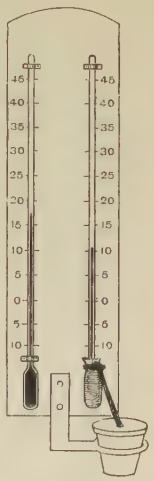


Fig. 49.—The psychrometer, or the dry-and-wet-bulb hygrometer.

In order to deduce the dew-point from the readings of the two thermometers, recourse is had to a set of tables known as Glaisher's Factors, because the factors in it corresponding to all the different temperatures of the dry-bulb were determined by J. Glaisher, F.R.S., by a long series of simultaneous observations of a dry-and-wet-bulb hygrometer and a dew-point hygrometer at Greenwich, and in India (for high temperatures), and at Toronto (for low and medium temperatures).

Some Examples from Glaisher's Table of Factors.

Reading of dry-bulb thermometer.	Factor.
30° F.	4·15
45°	2·16
54°	1·98
59°	1·89

To find the dew-point by means of the table, the rule is: *Multiply the difference between the temperatures (Fahrenheit) of the dry and the wet thermometer by the factor in the table opposite the temperature of the dry-bulb. Subtract this product from the dry-bulb reading, and the answer is the temperature of the dew-point.* For example, suppose the dry-bulb thermometer registers 54 F., and the wet-bulb 51° F.; then—

$$54^\circ - 51^\circ = 3^\circ$$
$$3^\circ \times 1{\cdot}98 = 5{\cdot}94^\circ$$
$$\therefore \text{dew-point} = 54^\circ - 5{\cdot}94^\circ = 48{\cdot}06^\circ \text{ F.}$$

Then, once the dew-point is known, the relative humidity of the atmosphere is obtained in the manner already explained.

The dry-and-wet-bulb hygrometer is very much used, as it has the great advantage that it works automatically, as it were; it requires no manipulation, and all the experimenter has to do is to take the readings. The indications of the instrument are considerably influenced by the action of draughts, but the greatest objection to it is that it fails to give reliable continuous records during frost, when the capillary action ceases and no evaporation takes place at the bulb. In such a case, a reading of the wet-bulb thermometer can be obtained by damping the frozen muslin with a brush that has been dipped into water, when evaporation takes place from the temporarily enlarged ice-covered bulb.

The Formation of Dew.—In 1814 Dr. Wells propounded the theory that the moisture deposited as dew is derived entirely from the atmosphere. He said that good radiators, such as vegetation, wood, glass, etc., fall in temperature rapidly during the night, so that the air in contact with them is cooled and rendered unable to retain the whole of its moisture, some of which is therefore deposited as dew on the cold objects.

Mr. John Aitken, F.R.S., however, has shown that, while part of the moisture comes from the atmosphere, by far the larger portion of the dew is caused by the condensation of water-vapour rising from the ground. He found that on dewy nights the ground under the surface is much warmer than at the surface, the difference sometimes being 10° or 18°; also the soil under the surface is always damp, as is readily seen on turning over a spadeful of earth. Hence vapour must be rising from the warm and moist soil, and a part of this vapour comes into contact with plants cooled by radiation and is condensed upon them in the form of dew. Also this moisture is considerably augmented by the condensation of the water-vapour exhaled from minute openings called *stomata* in the surface of

blades of grass and leaves of plants. His observations have since been confirmed and extended by others.[1] The following are a few of their experiments, which the student should repeat for himself and compare the results after calm clear nights and cloudy nights :—

1. Small squares of turf were cut out from a lawn, weighed, put back into their places, and weighed again in the morning when wet with dew. They were found to be lighter instead of heavier, as Wells's theory would require.

2. Glass vessels (such as tumblers) were inverted and placed upon grass, and upon bare earth. At the end of a clear night dew was invariably found on the interior of the vessels, and as there was always more dew on the inside of the vessels inverted over grass than on those over the bare earth, it was proved that some of the vapour was exhaled by the vegetation.

3. The experiments in No. 2 were repeated, but with metal or earthenware plates below the inverted vessels, and then dew was never found on the interior of the latter.

The Distribution of Rainfall may perhaps best be considered under the headings Geographical and Seasonal.

I. Geographical.

1. *The World generally.*—It is impossible, in the present state of our knowledge, to give an accurate account of the rainfall of the globe, for there are still immense tracts without observing stations, as, for example, in Africa, Central and Eastern Asia, British North America (except the province of Canada), the polar regions, and the oceans.

The student should have a general knowledge of the wettest and driest regions of the globe, and the reasons for their peculiarities (see *Elementary Physiography*, pp. 174–176). The following general statements may be made :—

(*a*) *The equatorial belt of calms*, lying a little to the north of the geographical equator, is said to be a region of heavy and constant rains, owing to the ascending movement of the air there laden by the great evaporation with moisture which is condensed in the cold upper air.

But while it is true as a general statement that this is the scene of almost continual rain, and contains some of the wettest regions of the globe, there are some places near the equator with a very slight rainfall, as, for instance, the island of Ascension with an annual rainfall of from two to three inches,

[1] J. Aitken, *Transactions Roy. Soc. Edin.*, vol. xxxiii. p. 9 (1885) ; also *Nature*, vol. xxxiii. p. 256 (1885). Colonel W. F. Badgley, *Quarterly Journal Roy. Met. Soc.*, vol. xvii. (1891). Hon. Rollo Russell, *Nature*, vol. xlvii. p. 210 (1892).

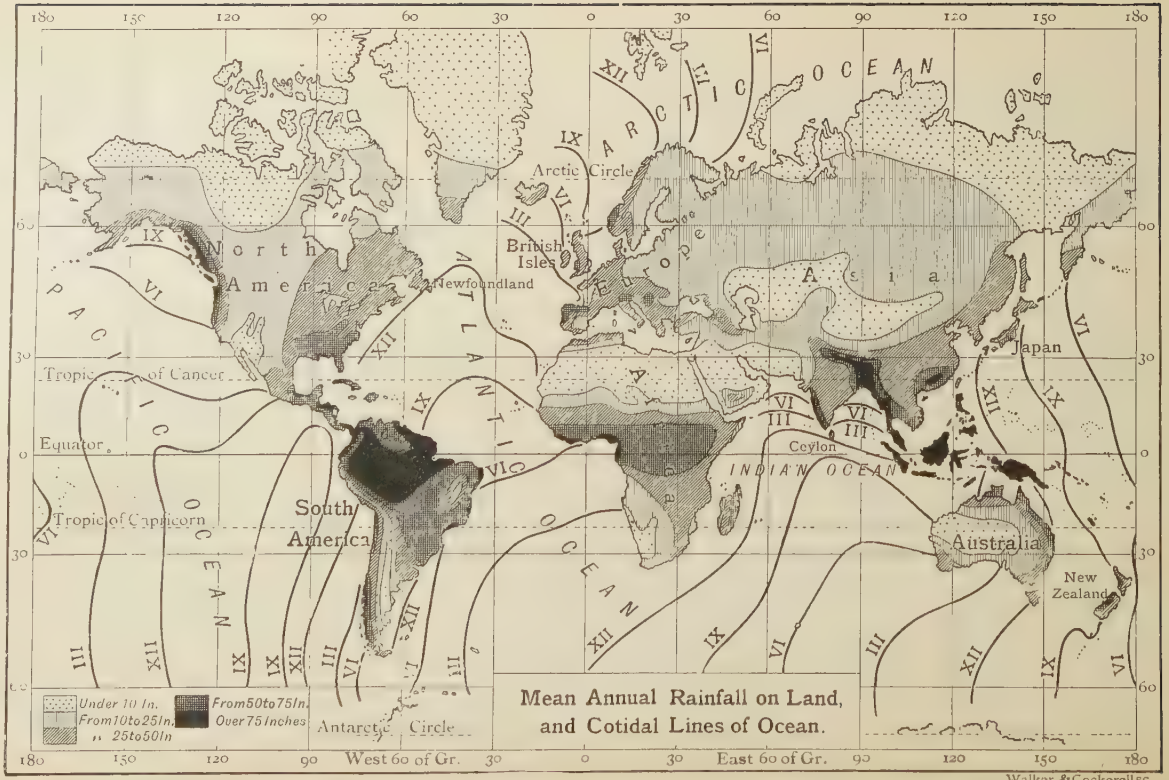


FIG. 50.—Mean annual rainfall for the continents, and co-tidal lines for the oceans.

and Malden Island and some other islands in mid-Pacific which are practically rainless, as is shown by their extensive guano deposits.

(*b*) *The Trade Wind regions* on both sides of this wet zone have comparatively little rain, as the winds are blowing towards the equator and so becoming warmer and more capable of retaining their water-vapour. But while the Trade Winds are essentially dry, they may deposit much moisture where they meet mountain ranges and are forced upwards. Thus the South-East Trade Wind deposits a great deal of moisture on the mountains of Eastern Brazil, and even on the eastern slopes of the Andes.

As the Trade Winds shift their position with the seasons, the dry areas shift also.

(*c*) *The regions of the Return Trades* in about latitudes 30° to 40° N. and S. have an abundant rainfall. The warm moist air which has ascended in the equatorial zone partly descends in the above latitudes once more to the earth's surface, and has some of its moisture condensed. In the northern hemisphere this region includes, for instance, California and Oregon, and the countries bordering the Mediterranean; and in the southern hemisphere Cape Colony, the south-west of Australia, and the North Island New Zealand.

(*d*) *The frigid zones* are comparatively dry, and the precipitation chiefly takes the form of snow. Sir John Murray has calculated that nearly 130 million tons of water are condensed from the atmosphere in a year, and of this not more than one-tenth falls as snow within the polar circles, while more than one-half falls as rain within the tropics.

2. *The British Islands.*—Owing in great measure to the efforts of the late Mr. G. J. Symons, F.R.S., the United Kingdom is now covered with a network of over 2000 rain-gauge stations, the results of the observations of which are published annually. The mean annual rainfall for our islands is about 35 inches. The chief rain-bringing wind comes from the south-west, and this fact, combined with the arrangement of the mountains, determines the distribution of rainfall. In Ireland the mountains are scattered pretty uniformly, and so is the rainfall, which averages 40 inches per annum, being greatest in the highlands of West Galway and the Killarney district (about 60 inches), and least in the neighbourhood of Dublin and in County Down (about 28 inches). In Great Britain the rainfall decreases from west to east. It averages nearly 80 inches in the

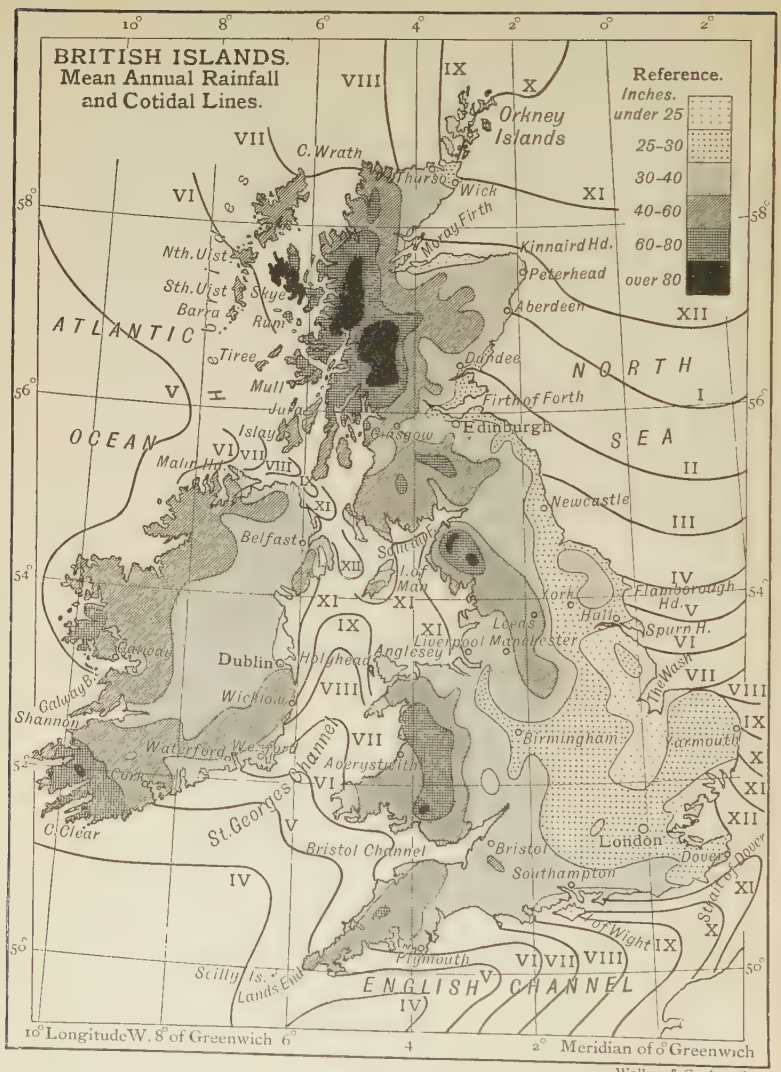


FIG. 51.—Mean annual rainfall of the British Islands, and co-tidal lines of the neighbouring seas.

Western Highlands of Scotland from Skye to Ben Lomond, the English Lake district, the mountainous districts of Wales, and the highest part of Dartmoor, in Devonshire. The wettest region in our islands—and indeed in Europe—is Seathwaite, in Cumberland, with a mean annual fall of 140 inches, and near Stye Head above it the average is 175 inches and in wet years it may be 200 inches. The driest district in our islands is the Eastern Counties between the Humber and Thames, in some parts of which the yearly rainfall is only 20 inches. On our west coast the average annual rainfall is over 40 inches, on the east coast 25 inches, and in the midland counties 25 to 30 inches. London and Edinburgh have a mean annual rainfall of nearly 25 and 26 inches respectively.

II. Seasonal.—The seasonal distribution of rain is hardly less important than the geographical, for the suitability or otherwise of a district for agricultural industry, or for particular crops, depends not merely upon the amount of rain that falls during the year, but at what times of the year the rainfall takes place. For instance, in one country the rain may fall during a wet season of short duration, and in another it may be pretty equally distributed throughout the year; or again, one region may have rain only in summer, and another only in winter, and maps like Figs. 50 and 51 can give no indication of these peculiarities :—

1. According to Mr. R. H. Scott, F.R.S., the rains of low latitudes are essentially summer rains.[1] The belt of calms oscillates on either side of the equator with the northern and southern summer, and the rains accompany the calms. Also the wet monsoons that prevail in some parts of this zone occur during the local summer.

2. According to the same authority, the regions of the Return Trades in both hemispheres have their rains in winter. For example, during the northern winter, when the sun is south of the equator, the N.E. Trades shift southwards also, and the northern region of the Return Trade moves south, carrying with it abundance of rain to regions that are at other times comparatively dry. Countries with winter rains and summer droughts can only be rendered productive by irrigation.

3. Further away from the equator in both hemispheres we come to the region of rain at all seasons. Our islands belong to this region, although on the whole they have the least rainfall in April and greatest in November.

Distribution of Temperature over the Globe in January and July.—If upon a map all places having the same mean temperature are connected by lines, such lines are

[1] *Elementary Meteorology*, p. 330.

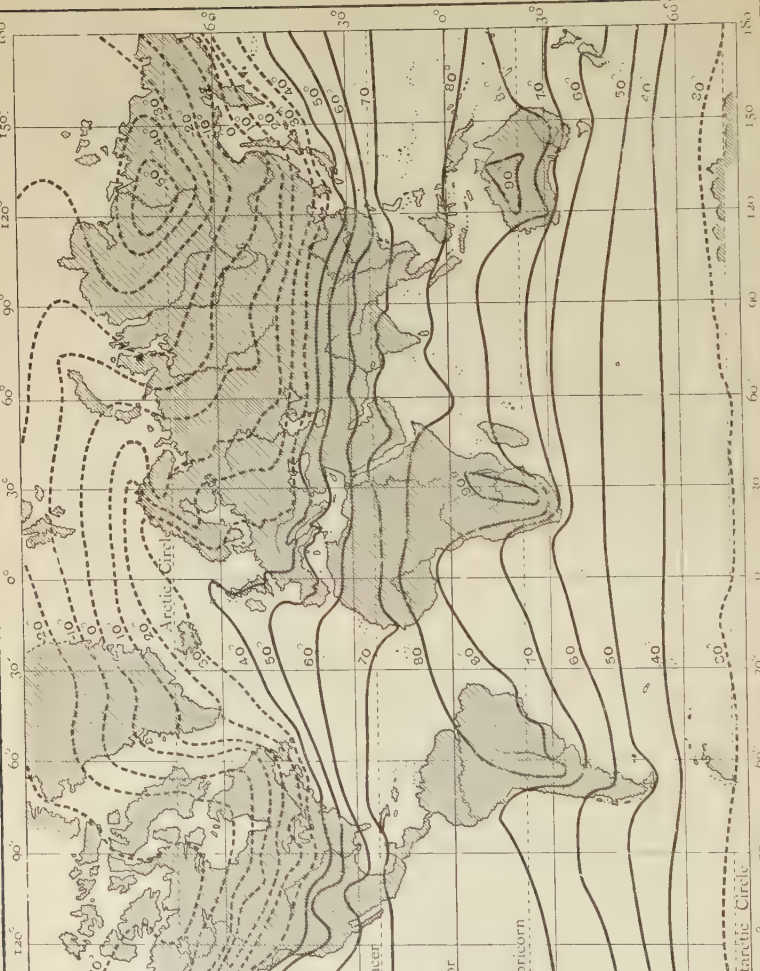


FIG. 52.—Isotherms for January, adapted from the *Challenger* Report. The numbers on the lines indicate the mean temperature for the month (reduced to sea-level) in degrees Fahrenheit.

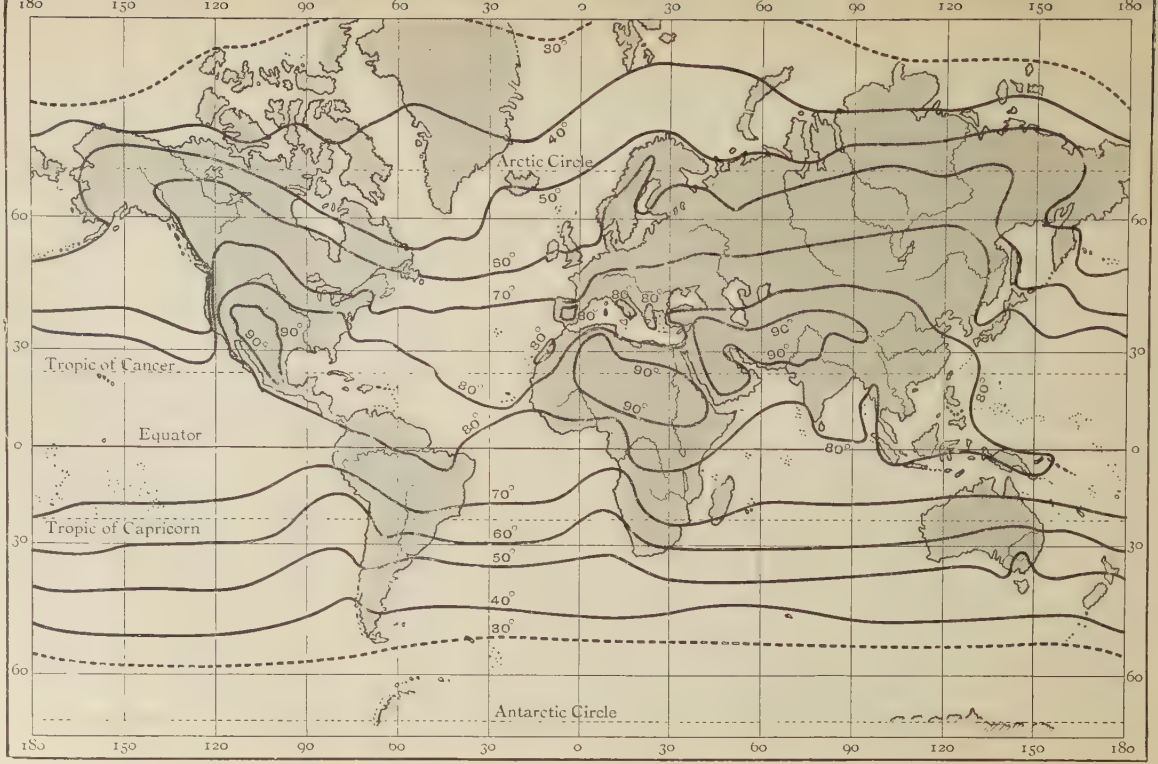


FIG. 53.—Isotherms for July, adapted from *Challenger* Report.

called "isothermal lines," and they are very useful for rendering obvious at a glance the distribution of temperature over the area embraced in the map.

For important remarks about isotherms, see *Elementary Physiography*, pp. 151–153. In Figs. 52 and 53 we have given the arrangement, according to the latest available information, of the isotherms over the globe in January and July. A comparison of the two charts suggests the following general remarks :—

1. In January the northern hemisphere has the land air in temperate and polar regions colder than the sea air in corresponding latitudes, for at this season the land loses more heat by radiation during the long nights than it receives during the short days, whereas the sea loses heat more slowly owing to its greater capacity for heat, and also to the fact that it is constantly receiving heat by warm currents from the equator.

July is the northern summer, and the land there is warmer than the surface of the sea in the same latitudes, but the difference is not very great, for the sea is also absorbing heat from the sun, and is in higher latitudes receiving heat from warm currents.

The difference between the temperature of the land air and sea air is not so great in the southern hemisphere either in summer or winter, owing to the smaller extent of land.

2. The distribution of temperature is seen in both maps to be much more regular in the southern hemisphere than in the northern, because the surface of the former is more nearly uniform, being almost entirely water south of 35° S. latitude. The only considerable irregularity in the southern isotherms occurs in the neighbourhood of land surfaces traversed by the Tropic of Capricorn.

The irregularity of the isotherms in the northern hemisphere is most marked in January, owing to the cooling of the land by radiation during the sojourn of the sun south of the equator. The isotherms in high latitudes are the most sinuous.

3. Both in January and July the western sides of the southern continents are colder than the eastern. For instance, in January the temperature of the west coasts of South America and of Africa on the Tropic of Capricorn is less than 70° F., and of their east coasts 80° F. The difference between the two coasts is due to the cold Antarctic current flowing along the western coasts of both continents, and partly also to the upwelling of cold water from below to replace the surface water driven seawards by the off-shore Trade Winds.

4. The ameliorating influence of the Gulf Stream and of the warm current flowing southwards along the west coast of North America should be observed. Notice how the isotherms crossing the Atlantic are bent northwards by the Gulf Stream, especially in January. For example, the Lofoten Islands off the coast of Norway, and the Siberian village of Verkhoyansk (lat. 67° 20′ N., long. 133° 30′ E.), are both in the same latitude and just within the Arctic Circle, yet owing to the Gulf Stream the January temperature of the former is above 32°, while that of the latter is −61° F.

5. The highest temperature marked on either map is 90° F. In January the only places warmer than this lie under the Tropic of Capricorn in Africa and Australia, while in July the regions warmer than 90° extend far north of the Tropic of Cancer in North America, Africa, and Asia.

It may be mentioned here that the highest authentic readings ever taken in the shade are 125° F. in the north-western parts of India, and 133° F. in the great African desert, while the lowest temperature yet observed was −89° F. at Verkhoyansk in January, 1886. The very low winter temperature of this place is due to its distance from the open sea being at that season greatly increased on account of the Arctic Ocean being frozen over.

6. A very important factor in determining the climate of a place is the range or amount of variation of temperature throughout the year. For example, London and New York have the same mean annual temperature, namely, about 50° F., yet their climates are very dissimilar, for London has a January temperature of 39°, and a July temperature of 64°, while for New York the corresponding temperatures are 30° and 75°; that is to say, London has an annual range of temperature of 25° F., and New York of 45° F.

By comparing the two figures, 52 and 53, we can tell the annual range of temperature at any given place. The following general statements are true:—

(*a*) Places in the northern hemisphere have on the whole greater ranges than in the southern, because of the disturbing influence of the large land surface in the former. In the north-east of Asia there is a range of 120° F., in North America of 80° F.; whereas south of the equator the greatest range is 30° F. in Australia, South America, and South Africa.

(*b*) The torrid zone is a region of small annual range of temperature, and the variations of temperature in the north temperate zone are much greater than in the south.

Sunshine.—The number of hours of sunshine during the day is a very important element in the climate of a place, and it depends, of course, upon the season of the year, the latitude of the place, openness of its position, its altitude, and the clearness or cloudiness of its atmosphere. One instrument employed for measuring the duration of sunshine is the Whipple-Casella Universal Sunshine Recorder, represented in Fig. 54. It consists of a glass sphere which acts as a lens to the sun's rays. Partially encircling the sphere is a frame supporting on the side next the sphere a strip of cardboard, which at all parts is at a distance from the sphere equal to its focal length. The sun's rays are focused by the sphere on the cardboard, which is in consequence charred or burnt at the point on which the sun's image falls. And as the sun passes from east to west between sunrise and sunset, the burning-point on the card is likewise shifted, so that a narrow strip is burnt out. When clouds intervene the continuity of this burnt strip is broken, and as the cardboard is divided so that definite sections of it correspond to certain hours and minutes, we can tell the duration of sunshine during the day. After sunset the card is removed, and a new one inserted ready for next day.

The instrument is called the "universal" sunshine recorder, because, as shown by the figure, it can be adjusted to suit any latitude and any day in the year.

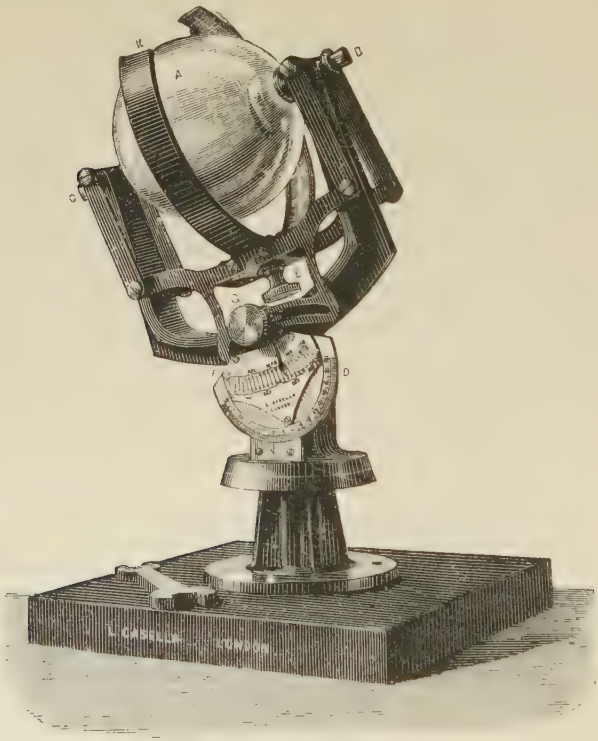


FIG. 54.—Whipple-Casella sunshine recorder.

QUESTIONS.

1. What is meant by the relative humidity of the atmosphere, and how is it determined?

2. What are hygrometers? Explain the construction and mode of use of some form of hygrometer.

3. What is the meaning of the term "dew-point"? How is the dew-point found? What use is made of it when it is found?

4. State what is meant by the "dew-point," and describe a dew-point hygrometer. How are observations made with this instrument, and what deductions can be drawn from the results of those observations?

5. Describe a series of experiments by which you would illustrate to a class the origin of dew.

6. Give an account of recent researches in connection with the origin of dew.

7. State briefly what you know regarding the distribution of rainfall.

8. What portions of the globe have rainy seasons, and when do these rainy seasons occur?

9. Explain the conditions which give rise to —

(*a*) Abundant rainfall.

(*b*) Great drought.

and give examples of districts characterized by —

(*c*) Excessive rainfall.

(*d*) Absence of rain.

10. Tell what you know regarding the rainfall of the British Islands.

11. Give a brief account of the distribution of temperature over the globe in January and July.

12. Explain what is meant by mean annual range of temperature, and mention a region where the range is small, and one where it is large.

13. Describe a method of recording the duration and intensity of sunshine on different days.

CHAPTER VIII.

ATMOSPHERIC PHENOMENA IN RELATION TO CLIMATE—(continued).

We have now to supplement what the reader should already know about the barometer and atmospheric pressure, and the method of indicating its simultaneous distribution over a large area by means of isobars (see *Elementary Physiography*, pp. 141–147). Barographs, constructed on exactly the same principle as the thermograph described on p. 28, are used in some observatories to furnish a continuous record of changes of atmospheric pressure.

The Aneroid Barometer is sometimes a convenient substitute for the mercurial barometer, because it contains no liquid, and hence its name (Gr. *a*, "not;" *neros*, "wet"). It consists essentially of a flat cylindrical box nearly exhausted of air, and then hermetically sealed. The top consists of very thin corrugated elastic metal. When the atmospheric pressure increases above what it was when the instrument was made the top is forced inwards, and when the pressure falls below that amount, the top is pushed out by a spring. These motions are transmitted to a pointer (by a system of delicate levers in a much more complicated manner than Fig. 55 indicates), which moves in one direction over a graduated scale with an increase of pressure, and in the opposite direction with a diminution. The graduation of the scale is made by trial to correspond with the inches of a standard mercurial barometer.

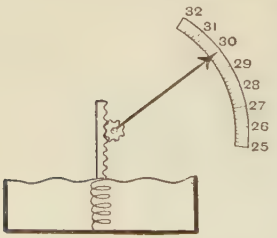


Fig. 55.—The principle of the aneroid barometer.

Aneroids have the advantages of being very sensitive and portable, but are apt to get out of order owing to rusting or loss of elasticity of the springs and levers, wherefore they

require to be periodically checked by a standard mercurial instrument.

Barometer Corrections.—Every barometrical observation must be corrected before we can compare it with readings taken at other times and at other stations, and therefore under different conditions. Some of the corrections are independent of the particular instrument used (*e.g.* correction for temperature, altitude, and gravity); others relate to the individual instrument (*e.g.* index error, capacity, capillarity).

1. *Correction for Temperature.*—The mercury in a barometer rises or falls with change of pressure and also owing to expansion or contraction of the mercury with change of temperature, and therefore instruments at two places might show different readings although the pressure was the same but the mercury at different temperatures. Hence, if we wish to compare the pressures at two places, we must first allow for the influence of temperature on the mercury, and this is done by reducing all barometric readings to what they would be at a standard temperature, viz. 32° F. As mercury contracts $\frac{1}{10000}$ part for every degree Fahrenheit of fall of temperature, the correction is to deduct $\frac{1}{10000}$ part of the observed reading for every degree that the temperature is above 32° F.; *e.g.* if the reading were 29·86 inches, and the temperature 60° F., then the corrected reading in inches would be—

$$29{\cdot}86 - \frac{28}{10{,}000} \text{ of } 29{\cdot}86.$$

For temperatures below 32° F. the correction must be added. The most of good barometers have brass scales, so that both the mercurial column and the scale expand and contract with variations of temperature, and the temperature correction for such instruments can be computed by a somewhat elaborate formula, or can be found at once from tables.

2. *Correction for Altitude.*—Since a barometer reads lower at the top of a hill than at its foot, before we can compare the readings of barometers at places with different altitudes we must reduce the readings to what they would be at a standard level, namely sea-level, which is taken as the level of the mean half-tide at Liverpool. The necessary correction is generally obtained from specially prepared tables. As the column falls roughly 0·1 inch for every 100 feet of vertical ascent, an approximate correction is to add 0·1 inch for every hundred feet vertically above sea-level. Suppose, for example, the reading to be 28·7 inches, and the altitude of the place 600 feet, then the corresponding reading for sea-level would be 28·7 + 0·6, or 29·3 inches.

3. *Correction for Gravity.*—Since the weight of a column of mercury is less at the equator than near the poles, it has been decided by an International Meteorological Conference to begin in the year 1901 the practice of correcting barometric readings to the force of gravity at lat. 45°. If g be the acceleration due to gravity at sea-level lat. 45°, and g' its value at the place of observation, then we multiply the actual reading by $\frac{g'}{g}$ to get the corrected reading.

4. *The index error* includes all errors made in the graduation of the scale.

5. *Error due to Difference of Capacity between the Tube and the Cistern.*—The level of the mercury in the cistern is constantly altering as the mercury rises and falls in the tube. But the rise of the mercury in the cistern is by no means equal to its fall in the tube (or *vice versâ*), hence the same difference of level between the mercury in the cistern and the tube does not always represent the same pressure. A correction for capacity, therefore, has to be made. This, however, is only necessary in old-fashioned instruments, as in modern ones like Fortin's barometer the mercury in the cistern is always brought to the zero of the scale before a reading is taken.

6. *Error due to Capillarity.*—Capillary action between glass and mercury depresses the column of mercury in the tube by an amount which depends on the size of the tube, being greater the smaller the diameter of the tube. In tubes more than half an inch in bore the depression is so small as to be negligible. In narrower tubes the amount that has to be added to the reading is obtained from tables constructed for the purpose—

e.g. in a tube whose diameter is 0·1 inch, the depression is 0·140 inch
,, ,, ,, 0·2 ,, ,, 0·058 ,,
,, ,, ,, 0·3 ,, ,, 0·029 ,,

The total amount of correction for the errors Nos. 4, 5, and 6 is entered on the certificate which accompanies a good instrument after it has been tested at an establishment like Kew Observatory.

Fluctuations in the Height of the Barometer.—At the equator the mean annual height of the barometer at sea-level is 29·84 inches. It increases from the equator, and between latitudes 30° and 40° attains a maximum of 30·04 inches, and then it decreases to the parallel 65° where it again begins to rise. At London the mean height of the barometer is 29·88 inches, and the mean for sea-level on the globe is 29·96 inches.

Atmospheric pressure is subject to two classes of variations —periodical and non-periodical. In our islands the former are barely noticeable, as they are masked by the frequent non-periodic changes. The regular or periodic variations are (1) diurnal, (2) annual; and the irregular or non-periodic variations are (1) cyclonic, (2) anticyclonic.

1. *The diurnal variation* takes the form of two maxima at about 9 a.m. and 9 p.m., and two minima at about 3 a.m. and 3 p.m. In our islands the daily range is not more than 0·03 inch, but within the tropics it amounts to more than 0·1 inch. Indeed, the diurnal variations of pressure are most marked within the tropics, where the causes that produce them are

most potent; they are less marked in temperate climates, and gradually sink to zero within the polar circles.

No explanation has yet been given which perfectly accounts for the diurnal variation of the barometer, and how its range varies with the seasons and latitude.

Dove's explanation is that the 3 p.m. minimum is due to the ascent and overflow of the air during the hottest part of the day; that the 3 a.m. minimum is caused by the diminution of pressure produced by the atmosphere having parted with a large amount of its water-vapour, which is condensed as dew by the nightly fall of temperature; that the 9 a.m. maximum is partly caused by the condensation of the air as its temperature fell during the night, and partly by the increased amount of water-vapour in the air owing to the rapid evaporation in the morning; and that the evening maximum is due to the rapid fall of temperature causing the air to become denser, coupled with the pressure of the large amount of water-vapour raised into the atmosphere by the evaporation of the daytime.

2. *The Annual Variation.*—As the heat of the earth's surface increases, the air over it ascends and overflows, and therefore we would expect the atmospheric pressure to be at a minimum in summer and a maximum in winter, and this is found to be practically the case over the land surfaces of the globe. But over the seas in higher latitudes, the yearly maximum is in early summer and the minimum in winter. From the analysis of a very extensive series of observations, Dr. Buchan concludes that "In the hemisphere where winter reigns, the greatest pressure lies over the land; the larger the continent the greater the pressure. In the hemisphere where summer reigns, the low pressures are over the land, the high over the oceans."

The range and time of the annual variation of pressure are different for different places, according to their circumstances. In our islands the highest readings are usually about the end of May or beginning of June, and the lowest at the end of October or early in November.

3. *Irregular Variations.*—Besides daily and yearly fluctuations of atmospheric pressure, there are irregular ones, due to cyclonic and anticyclonic conditions of the air. The lowest reading as yet observed was 27·124 inches, reduced to sea-level, at False Point, on the east coast of India, on September 22, 1885; and the highest 31·72 inches, at Semipalatinsk, in Western Siberia, on December 16, 1877. This gives a range of 4·6 inches, which is the greatest as yet observed at

the earth's surface. At London the greatest recorded range has been 3 inches.

Types of Isobars.—Lines drawn on a map through places having simultaneously the same atmospheric pressure, as measured by the barometer and reduced to sea-level and 32° F., are called isobars (see *Elementary Physiography*, pp. 146, 147). At the same hour each morning the height of the barometer and the temperature are telegraphed from a large number of places distributed over our islands and the adjacent parts of Europe, and then, after the barometric readings have been corrected for temperature and altitude, lines are drawn on a map joining places having the same atmospheric pressure at that time, the lines being drawn for inches and tenths of an inch of barometric height.

It is found that isobars may assume two primary and five secondary shapes, the general characteristics of each of which

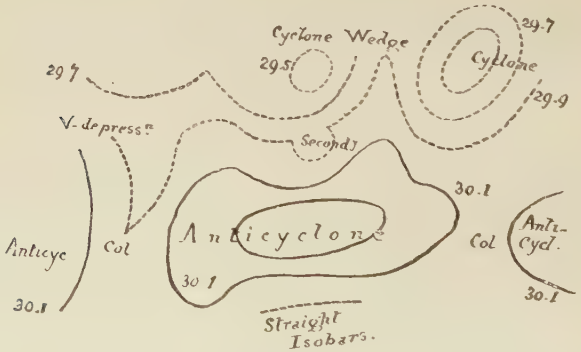


Fig. 56.—Diagram showing the chief types of isobars. (From Notter and Firth's *Hygiene*.)

will be understood from Fig. 56 and the following brief description :—

1. *Cyclonic.*—If the isobars form a series of more or less circular or oval curves enclosing an area of low pressure, outwards from which the pressure increases in all directions, they are said to be cyclonic in shape, and the locality of low pressure and the whole system connected with it are called a *depression* or *cyclone* (from Gr. *kyklos*, "a circle," because early observers believed that the wind blew round it in circles)

2. *Anticyclonic.*—If the isobars are closed curves similar in shape to the

above, but encircling an area of high pressure which decreases in all directions as we recede, they are said to be anticyclonic (Gr. *anti*, "in opposition to"), and the region of high pressure and the whole system connected with it are called an *anticyclone*.

The secondary types of isobars are modifications of these two. They are—

3. *Secondary cyclones or depressions*, which are areas of low pressure, having their isobars in the form of loops or incomplete concentric curves with the lowest pressure in the centre. They frequently occur on the outer edges of cyclones, with which they have many weather features in common.

4. *V-shaped depressions* are angular areas with the lowest pressure in the interior, and they frequently form between adjacent anticyclones. The isobars have the shape of the letter V.

5. *Wedge-shaped isobars* are also V-shaped, but are areas of high pressure between two adjacent cyclones. The wedge is usually just a projection from an anticyclone in the neighbourhood.

6. *Cols* are necks of comparatively low pressure between two anticyclonic areas. They are so called because they are analogous to the cols which form passes between adjacent mountains.

7. *Straight isobars* are, of course, those without any curvature. They may run straight, or nearly so, for hundreds of miles. They are only a temporary form, generally preceding the formation of a cyclone.

Barometric Gradient.—The closeness of the isobars to one another, that is, the rapidity of the change of pressure, constitutes what is called the barometric gradient, just as engineers use the word "gradient" to express rapidity of change of level along a slope. We express the gradient of a hill by saying that the ground rises so many feet in a mile, so *meteorologists in this country express barometric gradients as so many hundredths of an inch in* 15 *nautical miles* (which is the length of a quarter of a degree of a meridian). Thus a gradient of 4 means that the difference in atmospheric pressure is 0·04 inch in 15 nautical miles or about 17 ordinary miles. Suppose the barometric pressure at two places to be 29·72 and 29·16 inches, and the distance between them to be 119 miles; then the difference of the readings would be 0·56 inch, or 56 hundredths of an inch in 119 miles, or 8 hundredths in 17 miles, therefore the gradient would be 8.

When adjacent isobars on a map are far apart the barometric gradient is slight, and when they are crowded together a steep gradient is indicated. The pressure and velocity of the wind depend upon the steepness of the barometric gradient, being greatest at localities with the steepest gradient, and *vice versâ*; but no exact numerical relation has as yet been established between the gradient and the velocity or pressure of the wind.

The following may, however, be taken as approximately correct :—

Gradient.	Velocity of wind in miles per hour.	Wind.
0·5	7	Light breeze
3	25	Fresh breeze
7	50	Gale
15	80	Hurricane.

Buys Ballot's Law.—From the distribution of the atmospheric pressure we can also tell the direction of the wind by means of a law named after its discoverer, the late Professor Buys Ballot of Utrecht. It may be stated as follows :—

In the northern hemisphere, stand with your back to the wind, and the barometric pressure will be lower on your left hand than on your right; and in the southern hemisphere it will be lower on your right hand than on your left.

If the earth were not rotating, the wind would pass at right angles to the isobars from a region of high to one of low pressure, but because of the rotation of the earth winds are deflected, according to Ferrel's Law,[1] towards the right in the northern hemisphere, and towards the left in the southern, so that they cross the isobars at a small angle (varying generally from 10° to 30°, according to circumstances) towards the side of low pressure. Hence we might express Buys Ballot's Law more definitely thus :

In the northern hemisphere, stand with the isobars of low pressure on your left and those of high pressure on your right, then the wind will blow obliquely against the right side of your back. For the southern hemisphere the rule is the same as the above, with "right" and "left" interchanged.

Buys Ballot's Law enables us to predict the direction of the wind, and is indeed the fundamental law of modern weather-forecasting, hence the reader should impress the above statements on his mind by carefully studying Figs. 58, 60, and 62 to 65.

Measurement of the Direction, Velocity, and Pressure of the Wind.—The direction from which the wind is blowing is ascertained by means of a freely movable vane or weathercock. A wind-vane should be kept clear of buildings, trees, or anything likely to affect the direction of the wind; the gearing should be kept clean and oiled; and the cross giving the cardinal points should be fixed so as to give the true

[1] See *Elementary Physiography*, p. 191.

and not the magnetic bearings. If no vane is at hand, the drift of the smoke from a freely exposed chimney should be carefully noted.

Instruments for measuring either the pressure or the velocity of wind are called *anemometers* (Gr. *anemos*, "wind;" *metron*, "a measure"). The commonest form of velocity anemometer is that invented by the late Dr. Robinson. There is a vertical

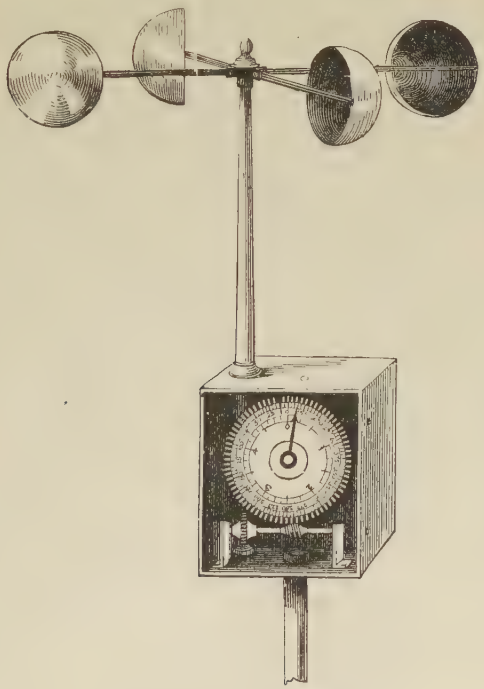


Fig. 57.—Robinson's anemometer.

axis which can rotate freely, and has fixed to its upper end four horizontal arms which form a square cross. At the outer end of each arm there is fixed a hollow hemispherical cup, as shown in Fig. 57. The wind drives the four cups round in a horizontal circle; this makes the vertical axis rotate, and its rotations are communicated by suitable mechanism to a dial,

which registers the number of rotations in a given time. According to Dr. Robinson, the cups travel at a rate equal to one-third that of the wind, and allowance is made for this in graduating the dial, so that the velocity of the wind at any particular time is found by observing the readings on the dial before and at the end of a certain interval of time, say, five minutes, in which case the velocity in miles per hour would be got by multiplying the difference between these two readings by 12.

Having obtained the velocity of the wind, its pressure can be got from the formula—

$$P = 0{\cdot}005V^2$$

that is, the pressure or force of the wind in pounds per square foot is equal to the square of the velocity in miles per hour multiplied by 0·005. Recent experiments by Mr. Dines show that 0·003 is more nearly the correct factor than 0·005.

To obtain good results from an anemometer, it must be kept thoroughly clean, well oiled, and should be placed in an open position about 20 feet from the ground.

Admiral Beaufort, in 1806, drew up a scale of numbers, still in use, to describe roughly the force of the wind, and the corresponding velocities and pressures have been calculated at the Meteorological Office, London, and we give them here for reference :—

BEAUFORT'S SCALE OF WIND FORCE, WITH EQUIVALENT VELOCITIES AND PRESSURES.

Beaufort's scale.	Description of wind.	Mean velocity in miles per hour.	Mean pressure per square foot.
0	calm	3	0·75 ozs.
1	light air	8	5·0 ,,
2	light breeze	13	13·5 ,,
3	gentle breeze	18	1·6 lbs.
4	moderate breeze	23	2·65 ,,
5	fresh breeze	28	4·0 ,,
6	strong breeze	34	5·75 ,,
7	moderate gale	40	8·0 ,,
8	fresh gale	48	11·5 ,,
9	strong gale	56	15·7 ,,
10	whole gale	65	21·2 ,,
11	storm	75	28·2 ,,
12	hurricane	90	40·5 ,,

Cyclones.—We have already defined a cyclone as a region of low atmospheric pressure with the lowest pressure in the centre, and shall now proceed to the study of this common form of atmospheric disturbance in more detail.

1. *The spiral motion of the wind around and towards the centre of low pressure* may be explained by Ferrel's principle (of which Buys Ballot's law is a particular case), for, according to it, a body moving on the earth's surface is deflected in the northern hemisphere towards the right by the earth's rotation, and to the left in the southern. Hence, when currents of air set in on all sides towards an area of low pressure in the northern hemisphere, they are all deflected in one way, namely, to the right, and the consequence is a counter-clockwise gyratory motion round the spot, as indicated in the upper part of Fig. 58. In the southern hemisphere the inflowing currents are all deflected to the left, and the spiral motion is therefore clockwise.

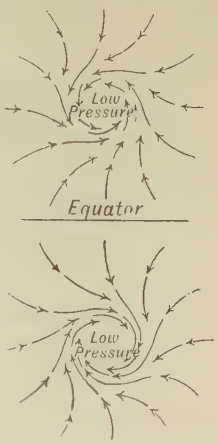


FIG. 58.—To explain the counter-clockwise spiral motion of a cyclone in the northern hemisphere, and the clockwise in the southern.

2. *The Onward Motion of Cyclones.*—The depressions do not remain in one spot. They have a forward movement, generally in the direction of the prevailing winds of the region. Hence between the tropics (the region of the Trade Winds) the motion is westward, but becomes eastward in the regions of the Antitrades by gradually turning, in accordance with Ferrel's principle, to the right in the northern hemisphere, and to the left in the southern. Over our islands, for example, cyclones generally travel from the south-west. The rate of advance varies within wide limits, and on the whole deep depressions travel faster than shallow ones. The average rate of onward motion of cyclones over Europe is from 15 to 30 miles an hour, while in America it is commonly as great as 50 miles, and occasionally even 80 miles, an hour. The rate of progress of cyclones within the tropics is, as a rule, slow—from 3 to 8 miles an hour—while the rotatory motion at the circumference may be from 80 to 800 miles an hour.[1]

[1] In a great gale on December 21–22, 1894, the velocity of the wind at

3. *Form and Size of Cyclonic Areas.*—Cyclones are usually oval and not circular in form, the major axis being generally less than twice the minor axis, and in our latitudes directed from W.S.W. to E.N.E.

The diameter of a cyclone is generally from 50 to 300 miles

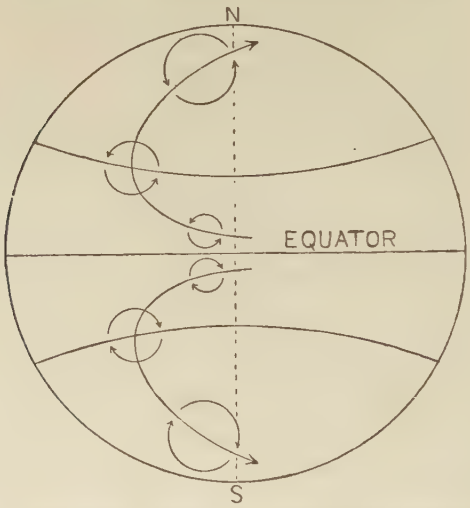


FIG. 59. To show the rotatory and the progressive motion of cyclones in the northern and southern hemispheres.

in length, but as the disturbance travels onwards it usually becomes more extensive, so that in high latitudes the diameter may be 1000 miles, 1500 miles, or even more. Indeed, the greater part of Europe or of the Atlantic is sometimes overspread by a single cyclone. When the dimensions of the storm become great, it frequently breaks up into two, three, or even more, separate cyclones.

4. *Region of Cyclones.*—Cyclones occur in all latitudes except within 5° of the equator. They are, however, much more frequent between the parallels of 40° and 70° than in other latitudes.

Fleetwood was 107 miles an hour, and for four consecutive hours exceeded 100 miles an hour. This is the greatest velocity of wind ever recorded in our islands. At Holyhead during the same storm, the wind in squalls attained a velocity of 150 miles an hour.

Cyclonic Weather.—The approach, passage, and departure of a cyclone are accompanied by definite changes in the weather, although the sequence of the changes at any one place depends, as will be shown, upon how it lies relatively to the centre of the storm. We shall, however, first describe the general characteristics of all cyclones, and the reader will understand the description better if he keeps in mind that at the centre of every cyclone the air ascends and overflows, and that the moisture in it is cooled by the ascent, and finally falls as rain.

Fig. 60 shows the form of the isobars, direction of the wind, clouds, and kind of weather in different parts of a cyclone in the north temperate zone. The long dotted arrow shows the direction in which the cyclone moves, and it is pointed to the east-north-east because that is the direction of motion of the majority of British cyclones. The short arrows indicate the direction of the wind, and a glance at the diagram shows that, broadly speaking, the wind rotates round the centre in a direction opposite to that of the hands of a clock. The isobars are much closer (*i.e.* the barometric gradient is steeper) in the rear than in the front of a cyclone, so that the strongest winds are behind the centre. The barometer gradually falls until the centre of the storm is reached, and then it rises more rapidly than it fell. The line of print at right angles to the direction of onward motion passes through the places at which the barometer is at its lowest point, and hence this line is called the "trough" of the cyclone, and the weather at all parts of it is squally, with sharp clearing showers. The part of the cyclone to the east of the trough is called the "front," and to the west of it the "rear." At the extreme front the increasing humidity of the atmosphere is indicated by the pale watery appearance of the sun or moon. By-and-by the sky becomes dirty and overcast, and a drizzling rain sets in, which soon develops into heavy driving rain. After the passage of the centre of the storm, the clouds break, patches of the blue sky are seen between the scudding cumulus clouds, and there are heavy squally showers. More of the rain accompanying a cyclone falls in the front than in the rear, and, owing to the great amount of heat liberated by the condensation, the air in the front part of the cyclone feels muggy and oppressive, whereas in the rear it is cool and bracing.

The ordinary sequence of weather at any place in the British Islands during the passage of a cyclone can, from Fig. 60, be seen to be somewhat as follows: The place will most

commonly be situated on the southern side of the track of the centre of the cyclone, for the majority of the cyclones that visit Western Europe pass with their centre to the north of our islands. Let P in Fig. 60 be a place south of the track of the

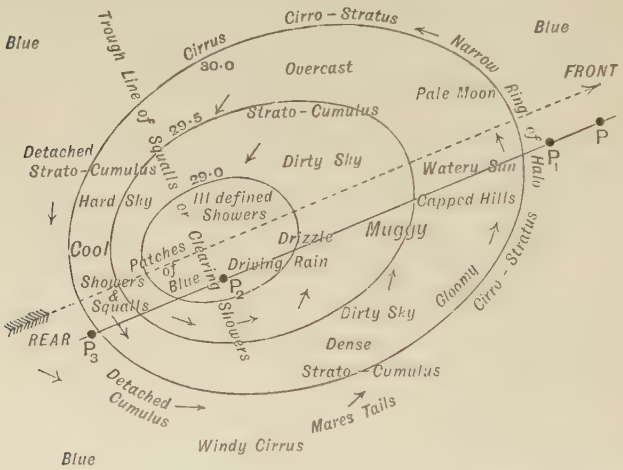


FIG. 60.—Diagram showing the direction of the wind, and the weather in the different parts of a typical British cyclone.

centre; then, as the cyclone moves onward, P will come successively into the positions P_1, P_2, P_3. As the barometer begins to fall, a halo may appear round the sun or moon, owing to reflection of light from the particles of ice formed by the condensation in the upper atmosphere of the moisture in the air ascending and overflowing from the cyclone, and a gentle wind will blow from the south-east. The sky becomes streaked with cirrus or cirro-stratus clouds, but soon it turns gloomy and watery, the air feels warm and oppressive even in winter, and the wind veers round and comes in fitful gusts from the south. If there be mountains in the neighbourhood, they get capped by mist or cloud. Then drizzling rain sets in, which gradually changes into a heavy rain driven before the wind, which has now veered round to the south-west and attained the force of a gale. When the trough of the cyclone reaches the place, the barometer is at its lowest, the rain heaviest, and with a squall the wind suddenly veers round a

number of points and becomes west or west-north-west. The barometer now begins to rise quickly and the thermometer to fall, the wind comes from the north-west and in stronger

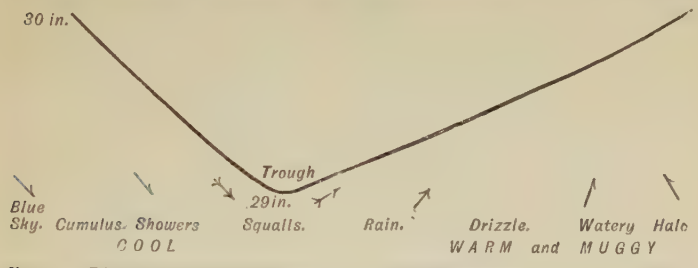


FIG. 61.—Diagrammatic representation of the weather-sequence in a typical British cyclone. The diagram is to be read from right to left.

squalls than before, the rain moderates into showers, patches of blue sky appear between detached hard cumulus clouds, and the atmosphere is cool and sharp. The showers by-and-by cease, the wind subsides to a breeze, and the sky is once more bright and cloudless.

All this sequence of weather is represented in diagrammatic form in Fig. 61. The heavy line represents the trace of a barograph during the passage of the cyclone, and observe that the gradient is much steeper during the rise than during the fall. The kinds of weather corresponding to the different heights of the barometer are written below. The arrows give the direction of the wind, and the number of barbs indicates the strength of the wind.

The reader should, from Fig. 60, describe as an exercise the succession of weather-changes at a place to the north of the track of the centre of the cyclone.

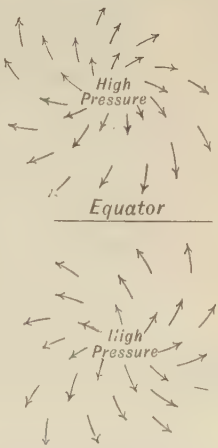


FIG. 62.—To explain the clockwise rotation of the wind in an anticyclone in the northern hemisphere, and the counter-clockwise in the southern.

Anticyclones have already been defined as regions of high atmospheric pressure with the highest pressure in the centre, and they are so named because they present us with conditions different in

almost every respect from those of cyclones. From the region of relatively high pressure winds blow outwards in all directions, and by Ferrel's or Buys Ballot's law they are deflected to the right of an observer at the centre of the anticyclone in the

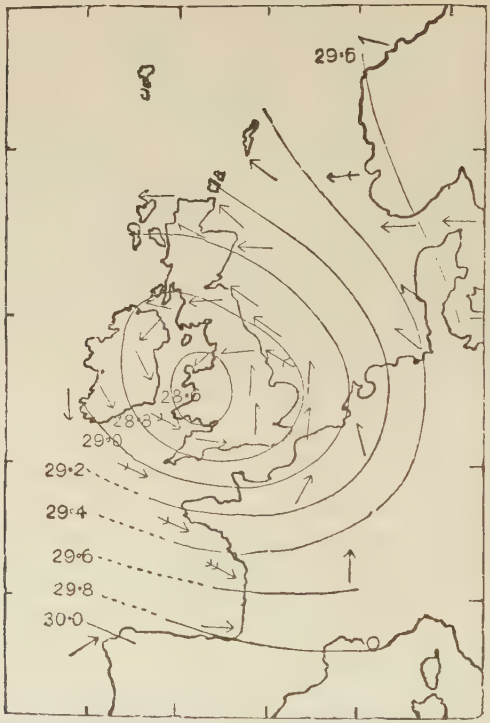


Fig. 63.—Cyclonic system of isobars and wind (November 29, 1874, 8 a.m.). (From Scott's *Weather Charts*.) The arrows are thus distinguished according to Beaufort's scale, p. 120 :—

Beaufort's scale.		Miles per hour.
1–4	→	8 to 23
5–7	⇒	28 to 40
8–10	⇒	48 to 65

northern hemisphere, and to the left in the southern; consequently the circulation of wind round the edge of an anticyclone north of the equator is in the same direction as the hands of a clock move, and in the opposite direction in the southern hemisphere (Fig. 62).

Anticyclones, as a rule, do not move onwards; the isobars may remain stationary for days or even weeks on end. The gradients are invariably slight, so that the wind is scarcely perceptible. Since in an anticyclone the surface winds pass

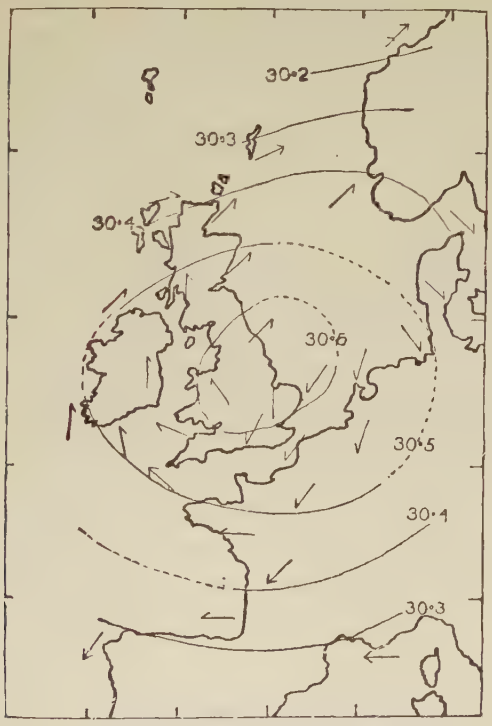


FIG. 64.—Anticyclonic system of isobars and wind (February 4, 1874, 8 a.m.). (From Scott's *Weather Charts.*)

outwards, there must be a continual descent of air from above to take their place. The descending air will contain very little moisture, and as it is heated by its descent to the earth's surface, it becomes relatively drier. Hence the weather accompanying an anticyclone is clear and dry, except for the occasional formation and clearing away of haze or fog. Because of the dryness of the air, solar and terrestrial radiations

pass freely through it; hence anticyclonic weather, which is always clear and calm, is associated in summer with great heat during the day, and haze or heavy deposits of dew at night. In winter the rapid radiation from the earth's surface, especially during the night, causes the temperature of the air to fall, and hence anticyclones during this season are accompanied by great cold, and sometimes give rise to long spells of hard frost. Therefore anticyclones bring the hottest weather in summer and the coldest in winter.

Cyclones and Anticyclones contrasted.

Cyclones.	Anticyclones.
Winds.	
1. Isobars lie close together, gradient steep, winds strong—sometimes hurricane force.	1. Isobars lie far apart, gradient gentle, and winds light and variable.
2. At the earth's surface the wind is flowing in a *counter-clockwise* course (in northern hemisphere) *into* area of low pressure, whence it rises into upper regions of atmosphere and overflows.	2. At the earth's surface the wind is flowing in a *clockwise* course (in northern hemisphere) *out of* area of high pressure, into which it has descended from the upper regions of the atmosphere.
3. A cyclonic system as a rule travels, it may be at a rate of 20 miles an hour or more, in the direction of the prevailing winds of the region.	3. An anticyclonic system is often stationary for days or weeks, or its motion is slow and irregular.
Weather.	
4. Unsettled, windy, cloudy, damp. Violent shifts of wind; usually great changes of temperature—warm during first half, cool during second. Heavy squalls. Thunderstorms (especially in summer). Heavy showers of rain and hail in summer, and snow in winter.	4. Settled, calm, clear, dry. In summer, hot sunshine by day and cool dewy nights owing to radiation, and sea-fogs if centre over sea. In winter, cold frosty weather if sky clear, but sometimes dense fogs.

Causes of Cyclones and Anticyclones.—There is no doubt that these, like all other kinds of distribution of pressure, are primarily due to the unequal heating of the surface of the earth by the sun's rays in tropical and polar regions, but how this operates so as to produce the characteristics of cyclones and anticyclones is still a matter of discussion. There are two main theories:—

1. *The Convection Theory.*—Land and water, dry and marshy areas, cultivated and barren districts have different absorptive and radiating power for the sun's rays, and hence it may happen that a limited part of the earth's surface may become more heated than surrounding parts, and a convection current of heated air will ascend there and overflow on surrounding regions. As the air ascends it will become cooled and its moisture will be condensed, and the latent heat set free will further rarefy the air and increase the updraught. The atmospheric pressure on the region over which the air is

ascending and spreading outwards will be diminished, hence air will flow in from all sides towards the area, and a cyclone is produced; whereas the surrounding regions on which the air overflows must have their pressure increased, hence currents will flow outwards in all directions, and an anticyclone is produced.

The above explanation might account for tropical cyclones, but it is not so satisfactory for the cyclones and anticyclones of temperate regions, where the sun's heat is much less, and where cyclones are more frequent and more violent in winter than in summer.

2. *The Eddy Theory*,[1] advocated by Professor Hann at Vienna in 1890, seems to have the greater weight of evidence in its favour, at least for the cyclones and anticyclones of temperate and sub-polar regions. According to the convection theory cyclones have their primary impulse in the surface air, whereas according to the eddy theory they originate in the higher atmosphere. Upper currents proceed from the equator towards the poles, and as they do so they must converge owing to the continuously smaller radius of the parallels of latitude they are reaching, and hence the air becomes banked up, as it were, and causes anticyclonic areas of high pressure. But the poleward currents are also deflected towards the east by the earth's rotation, and therefore their congestion is somewhat irregular, and this gives rise to vertical eddies between the currents. These great whirls extend down to the earth's surface, and will necessarily be centres of low pressure, towards which streams of air will flow from all sides and ascend through the vortex and have their moisture condensed. "What particular circumstance causes them to originate in one place rather than in another we can scarcely say, any more than we can say how each eddy originates in a rapidly flowing deep river. Some very small inequality of pressure probably starts them; but, once formed, they often last for many days, and travel some thousands of miles over the earth's surface."

It is unnecessary for us to discuss the claims of the rival theories. Probably cyclonic and anticyclonic systems may originate sometimes in the one way and sometimes in the other, and it is probable that the first theory is the most likely one for the majority of tropical cyclones, and the second for extra-tropical ones.

Storms.—A storm is a general term for a disturbance of any of the meteorological conditions, such as wind, rain, hail, snow, etc. The following are a few of the commonest forms of storms, in addition to cyclones which we have already fully described :—

Hurricanes.—Certain parts of the tropics, especially the West Indies, the Bay of Bengal, and the Indian Ocean, are subject during the summer and autumn months to storms which only differ in violence from the cyclones of the temperate zones. In these tropical cyclones, also, the areas are less, the barometric gradients much steeper, and consequently the force of the winds round and towards the centre is sometimes enormously greater than in our latitudes, while the rate of onward movement is less. Other minor differences are that at the centre of a hurricane the weather clears, and there is a patch of blue sky known as the "eye of the storm," and that there is not the difference in the kind of weather in the rear and front of the storm that there is in a European cyclone. In the West Indies hurricanes occur chiefly between July and October. In the China Sea they are frequent during the same period, and are known as *typhoons*. Storms of the same name occur in the Indian Ocean at the change of the monsoons.

[1] An account of it is given in *Nature*, November 6 and 27, 1890.

Tornadoes are storms of a somewhat similar nature, but of smaller extent —usually less than two miles in diameter—and more concentrated. They are whirling funnel-shaped masses of air with the narrow end of the funnel reaching to, or near to, the earth's surface. Measurements show that in tornadoes the rotatory motion varies from 100 to 500 miles an hour, the latter velocity producing the enormous wind-pressure of 750 lbs. per square foot. Besides the whirling motion there is also a rapid ascending motion up the centre of the funnel. Such storms travel bodily onwards an average distance of about 25 miles, at rates varying from 10 to 100 miles an hour. They sometimes draw up into the vortex trees, men, animals, etc., and fling them with great force to a considerable distance. Storms of this nature cause waterspouts when passing over sea, and sandspouts when over land. There has been much controversy as to the origin of a tornado, and it would be well not to confound them with small cyclones. A tornado seems to be caused by a lofty column of saturated air becoming rapidly heated by absorption of the sun's rays. The column of air, being thus rarefied, rises with a gyratory motion and draws the surface air in from all sides towards the partial vacuum. This air rushes in with terrific violence and ascends with a whirling motion.

Whirlwind.—This name does not denote any special kind of wind, but is applied to any rotating mass of air, whether its diameter be great or small, and thus it includes anything from a tornado down to the familiar dust-whirl on a dry road.

Squalls are of various forms, and much has still to be learnt as to their true nature. They appear to be caused by the cold dense upper layers of air for some reason suddenly breaking through the warmer layers below. The *white squall* is so called from its covering the sea with white foam.

Questions.

1. Describe the principle of the construction of the aneroid barometer.
2. What are the chief corrections to be applied to the readings of a barometer? Explain why these corrections are necessary, and how they are made.
3. Explain why the following corrections are necessary for a barometer-reading: (*a*) Height of place of observation; (*b*) temperature at time of observation.
4. I wish to compare the barometric readings taken at two places: what data with respect to these places will it be necessary for me to have, and why?
5. Describe the change in barometrical pressure as we ascend in the atmosphere, and state its cause.
6. Tell what you know about the diurnal and annual variations in atmospheric pressure.
7. What are isobars, and what are their chief types? State the causes to which their continual changes in position are due.
8. Carefully explain what is meant by a "barometric gradient." What is decided by the steepness of such a gradient?
9. If the barometer at one place reads 29·14 inches, and at another 34 miles away it reads 29 inches, what is the barometric gradient between them?
10. On February 1, 1868, during a tremendous westerly gale, the readings at Rochefort and Aberdeen were 30·16 inches and 28·40 inches

respectively, and the distance between the two places is 673 miles ; what was the gradient ?

11. State Buys Ballot's law.

12. How are the direction and force of the wind measured ?

13. State what you know of cyclones and anticyclones, the direction in which they move, and the way in which they are formed.

14. What do you understand by the terms anticyclone and cyclone ? Explain carefully the distribution of barometric pressures in the areas where such phenomena are being manifested.

15. Compare and contrast the phenomena associated with cyclones and anticyclones.

16. What are the probable causes of a cyclonic disturbance ?

17. How may the approach of a cyclone be noted ? In what parts of the world are cyclones most destructive ?

18. Give a brief account of the chief varieties of storms.

CHAPTER IX.

WEATHER AND CLIMATE.

Weather Charts.—The weather of any region is mainly determined by the pressure of the atmosphere, force and direction of the wind, the temperature of the air, humidity, clouds, etc. Hence the instruments indispensable at a meteorological station are a standard barometer, maximum and minimum thermometers, a dry-and-wet-bulb thermometer, and a rain-gauge. The above four thermometers must be placed in the shade, and therefore, for comparison with other places, they are suspended in a box called Stevenson's Thermometer Screen, which is placed at a height of four feet from the ground, and, in order to freely admit the air, has its sides louvred, that is, consisting of strips of wood arranged like a half-open venetian blind. In addition to the above instruments, it is desirable to have at a meteorological station also an anemometer, a sunshine recorder, a solar-radiation thermometer (that is, a black-bulb maximum thermometer *in vacuo*). As far as possible the instruments should be self-registering so as to keep a continuous record, and all of them should have been verified at Kew Observatory, that their amount of error may be known.

Stations equipped as above have been established in various parts of our islands and adjacent parts of the continent. The observations are made almost totally by volunteers, but the stations are regularly visited by inspectors from the Central Meteorological Office in London, maintained by Government. Every morning at 8 a.m. and evening at 6 p.m. observations are made of atmospheric pressure, maxima and minima of temperature, dry-and-wet-bulb, rainfall, wind, and cloud, and these, along with general remarks on the weather, are telegraphed to the Meteorological Office. Here the results are corrected to their value at sea-level, and weather charts (called *synoptic charts*, from Gr. *synopsis*, "a collected or general view") are prepared showing at a glance the atmospheric pressure and probable weather at the different places, and

forecasts based on the morning and evening reports are issued at 11 a.m. and 7.30 p.m. (and during June, July, and August at 3.30 p.m. also) for each of the eleven districts into which our islands are divided for this purpose.

The weather at a place depends chiefly on the distribution of atmospheric pressure over a large area round about it, and indeed modern weather forecasting is based on the recognition of the fact that each of the seven different types of isobars is accompanied by a special kind of weather, which we have fully described for the two most important types—cyclonic and anticyclonic. British weather varies mainly with the passage of cyclones eastward from the Atlantic. But we have seen that each division of a cyclone has weather features special to itself, and that when a cyclone passes over a place a certain sequence of weather is displayed. From the data supplied by the outlying stations, the meteorologist draws the isobars of the cyclone, and can fill in the kind of weather in its different parts. If he likewise can determine the direction and rate of its forward movement, and how the barometric gradient is altering, that is, whether the depression is deepening or filling up, then he can foretell the weather at the various places over which the cyclone will pass.

All this, of course, requires great skill and experience on the part of the forecaster, and even then the prediction may not be fulfilled owing to an unusual change in the direction and velocity of the cyclone's motion, or the barometric gradient may alter unexpectedly, or a secondary depression may suddenly form at a place not anticipated. Also meteorologists are handicapped by the fact that on the west (the side from which our weather-changes usually come) we have no stations nearer than America, and that our islands are situated on the margin between a great extent of ocean to the west and continent on the east, and are thus subject to sudden changes in the weather for which no warning is possible. Considering all these drawbacks, it is creditable that fully 80 per cent. of the official weather forecasts are successful.

Weather reports and forecasts from the Meteorological Office appear in all the morning and evening papers, but only the *Times* prints a daily synoptic chart of our islands. Fig. 65 is the one issued on the first day of this century.

Climate is the average weather of a locality. Like weather, it embraces all meteorological phenomena, more particularly as to their effects upon animal and vegetable life. Its most important factors, however, are (1) the mean annual temperature, and the summer and winter temperature; (2) the mean annual rainfall and its distribution throughout the year;

and (3) the amount of sunshine. The diversities of climate depend chiefly on the combined operation of four causes: (1) latitude, (2) altitude, (3) distance from the sea, (4) the

In the above chart the dotted lines are "isobars," or lines of equal barometrical pressure, the values which they indicate being given in figures at the end, thus—30·4. The shade temperature is given in figures. Light wind, ⟶; fresh or strong, ⟶; a gale, ⟶⟶.

FIG. 65.—The *Times* weather chart, Jan. 1, 1901.

prevailing winds. Other causes that affect climate are (5) ocean currents, (6) annual rainfall, (7) height and direction of neighbouring mountain chains, (8) aspect and general slope of the ground, (9) nature of the soil, (10) degree of cultivation of soil. We shall briefly treat of these in turn:—

1. **Latitude** is the most important factor in determining the mean annual temperature of a place, for on it depends not only the duration of sunshine, but also the heating power of the sun's rays. As explained in *Elementary Physiography*, p. 150,

the nearer a place is to the equator the more perpendicularly a sunbeam falls on the ground, and, being spread over a small area, is more concentrated, and also having a shorter path through the atmosphere less of the heat of the beam is absorbed by the air before reaching the earth.

2. **Altitude.**—The climate of highlands has certain peculiarities which distinguish it from that of adjacent lowlands—

(*a*) *The mean annual temperature is lower.* This is because the air is less dense, clearer, and contains less water-vapour, and consequently it absorbs less of the heat of the sun's rays while passing through it, and intercepts less of the heat radiated by the earth. The rate at which the air becomes cooler with elevation varies at different places, and at different times at the same place, but for moderate altitudes the general average is about 1° F. for every 300 feet of vertical ascent, so that at an elevation of, say, 4500 feet the mean temperature would, in round numbers, be 15° F. lower than on the plains beneath. For instance, Quito, the capital of Ecuador, at an altitude of fully 9000 feet, enjoys perpetual spring, with a steady temperature of about 60° F., although almost on the equator. Similarly, in India a bracing climate is obtained at a height of about 3000 feet, and Europeans recruit their health by retiring for a time to the sanatoria (*e.g.* Simla, 7000 feet high) on the Himalayas and Neilgherries.

(*b*) *There is a greater difference between the temperature of the atmosphere and that of the earth's surface.* The ground and objects directly exposed to the sun's rays may have a pretty high temperature, while the atmosphere itself is cold.

(*c*) *The range of temperature is greater at elevated stations than at sea-level.* For instance, Madrid is nearly in the same latitude but at a much higher level than Lisbon, and its annual range of temperature is nearly twice as great. This is also, of course, partly owing to greater distance from the sea.

(*d*) *The mean annual rainfall increases up to a certain altitude, above which it diminishes.* The elevation at which maximum rainfall takes place varies greatly with locality, depending on the direction of the slope to the rain-bringing winds, the trend of the valleys, etc., but it may be stated as 3000—4000 feet in winter, and higher in summer.

3. **Distance from the Sea.**—All expanses of water temper extremes of climate, rendering it less hot in summer and less cold in winter. The reasons for this are—

(*a*) *The specific heat of water* is about four times that of dry land—that is, it

requires four times as much heat to raise the temperature of a certain mass of water 1° as to heat an equal mass of land the same amount. Hence the temperature of the sea will rise more slowly in summer, and fall more gradually in winter, than will that of the land.

(*b*) *Penetrability to heat-rays.* The heat of the sun penetrates into the earth only 70 or 80 feet, whereas the solar rays penetrate into the sea the same number of fathoms, and even below this, down perhaps to 500 fathoms, the temperature is affected by surface currents traceable to the energy of the sun.

(*c*) *Physical condition.* Since the sea is liquid, there is continual motion going on in it, thus mixing the warmer and colder water and equalizing temperature. This, of course, is not possible in the solid land.

(*d*) *The dryness of the air over large areas of land* causes it to be more rapidly heated in summer and cooled in winter than the moist air over water-surfaces.

For these reasons the sea is less readily heated and cooled than the land, therefore its temperature is much more equable, and since the air acquires its temperature mainly from the surface on which it rests, the climates of the oceans and the continents show the same difference, and the climates of inland localities invariably have a greater annual range of temperature than those of seaboards in the same latitude. To give but one example, the Lofoten Islands off the coast of Norway and Verkhoyansk in Siberia have the same latitude, but at the former the annual range is only 20° F., and at the latter no less than 116°, this being, indeed, the greatest annual range known.

An exceedingly useful exercise to enable the reader to fully appreciate how greatly land and sea affect climate would be to follow carefully the course of the isotherms that pass through the British Islands, namely, 40° in Fig. 52, and 60° in Fig. 53, observing carefully their latitude in mid-ocean, near the coast, and in the heart of the continents.

4. **Prevailing Winds.**—Climate is mainly determined by the temperature and moisture of the air, and hence it is very greatly influenced by the prevailing winds, which are charged with the temperature and moisture of the regions from which they come. Winds raise or lower the temperature of a place according as they flow from the equator or from the poles. Winds from the ocean are laden with water-vapour which interferes both with solar and terrestrial radiation, and therefore sea-winds render the climate cool in summer and mild in winter, whereas dry winds from continents change their character with the seasons, being hot winds in summer and cold winds in winter. Again, moisture-laden winds raise the

temperature because the latent heat of the vapour is given out during the process of condensation. Finally, it must be remembered that the prevailing winds determine in large measure the currents of the ocean, which, we shall see, powerfully influence climate.

The isothermal charts (Figs. 52 and 53) offer striking evidence of the influence of winds on climate. Observe, for example, the influence of the south-west Antitrades in raising the temperature of the west coasts of Europe and America far above the corresponding parts of the east coasts. Or, in our own islands, consider the difference between the warm and moist south-west wind, which is equatorial and oceanic, and the cold and parching north-east wind, which is northerly and continental.

5. **Ocean Currents** may bring water much warmer or colder than that naturally belonging to the latitude. The temperature of the overlying air will be correspondingly influenced, and if this air is carried inland by winds the climate there will be affected. In Figs. 52 and 53 the influence of the warm and cold ocean currents can be very distinctly traced. Because of the westward equatorial currents, the east coasts of South America, Africa, and Australia are warmer than the west. It is in the North Atlantic, however, that the effect of currents is most strikingly seen. The cold Labrador current, flowing southward from the Arctic Ocean along the north-east coast of America, lowers the mean annual temperature of that region, while on the other side of the Atlantic the Gulf Stream raises the temperature of the whole of the north-west of Europe. For instance, Dublin and the south-east corner of Labrador are in the same latitude, yet their mean annual temperatures differ by 18° F., being respectively 50° and 32° F. If by any change in the configuration of the continents the Gulf Stream were to be diverted from its present course, the coasts of Britain and Norway would be ice-bound in winter. For example, the mean winter temperature of London, so far as latitude is concerned, should be 22° F., and of Shetland 7°·5 F.; whereas, mainly owing to the influence of the Gulf Stream, their actual mean winter temperatures are respectively 39° and 39°·5 F., London thus benefiting by 17°, and Shetland by 32° F.

6. **Annual Rainfall.**—Rain raises the temperature of the atmosphere by the vapour giving up its latent heat. The Rev. Dr. Haughton calculates that one gallon of rainfall gives

out latent heat sufficient to melt 75 lbs. of ice, and from this datum he concludes that on the west coast of Ireland the heat derived from the rainfall is equal to half that got directly from the sun.

7. **Direction of Neighbouring Mountain Chains.**—The effect of mountain ranges depends upon whether they trend more or less directly across or parallel to the prevailing winds. The latter is the case with the Alps and Appalachians, and they have no distinctly wet and dry sides. But when the prevailing winds blow across a mountain chain, the opposite sides have different climates. The windward side is moist, and the formation of clouds and mists checks radiation and therefore moderates the range of temperature by day and night, summer and winter. On the other hand, the leeward side is dry, and as the wind descends to warmer regions it has its relative humidity decreased. The dry air and cloudless sky allow great heating by the sun during the day and rapid cooling by radiation at night, and similarly cause hot summers and cold winters. This is one of the causes to which we owe the difference between the climates of the west and east coasts of our islands.

8. **The exposure or direction of slope** in hilly regions determines the angle at which the sun's rays reach the surface, and we have already explained how this influences the amount of heat imparted to the ground, which in turn affects the temperature of the overlying air, and therefore the climate. In our hemisphere the southern slopes receive the sun's rays more nearly perpendicularly, and for a longer time each day, and hence they are warmer than the other slopes. The southern slopes of the Alps, for example, have a much more genial climate than the northern. In the southern hemisphere, on the other hand, the northern slopes of hills are warmer.

9. **Nature of the Soil.**—A clayey, dense, impermeable soil makes the atmosphere moist, and lowers the average temperature, while sand and loose permeable soils have the opposite effect. Moreover, marshy or fertile districts have much more equable climates than dry barren districts, for sandy and rocky surfaces are subject to great diurnal range of temperature, being extremely hot by absorption during the day, and ice-cold by radiation during the night.

10. **Vegetation.**—The effect of drainage and cultivation of the soil is to render climate drier and warmer. It is said, for instance, that the mean annual temperature of Great Britain

has been raised one or two degrees by the extensive drainage that has gone on during the last century. But plants render climate more uniform and temperate in other ways, for by day they intercept a large proportion of the sun's rays that would otherwise heat the earth's surface, and also the evaporation going on from their leaves keeps the atmosphere cool, and by night they check the rapid cooling of the ground by radiation.

Influence of Forests on Climate.[1]

(*a*) *As regards Soil Temperature.*—The mean annual temperature of the soil in a forest is lower than in the open.

(*b*) *As regards Atmospheric Temperature.*—The temperature of the air is rendered more uniform, the influence of the forest being to lower the maximum and raise the minimum temperatures. In forests it is cooler during the day and warmer during the night than in the open, for during the day the shade of the trees keeps the air from being rapidly warmed by the sun's rays, and during the night the trees check the radiation.

(*c*) *As regards Rainfall.*—Since the air in the forest and the trees themselves are cooler during the day than the air in the open, it follows that if a current of air is wafted from the open into the wood it is cooled, and thus has its relative humidity increased, and if the air be reduced to its saturation point, then the moisture will be deposited as dew or rain. Felling forests undoubtedly diminishes the rainfall, and makes it more irregular and causes droughts (as has happened in some parts of India, China, Canada, etc.), while the afforesting of treeless lands gradually increases the rainfall in regularity and amount.

Classification of Climates according to Annual Range of Temperature.—On account of the great influence of extensive water or land surfaces upon the fluctuations of temperature, climates are divided into—

1. *Oceanic or insular climates*—those whose annual range of temperature is small because the proximity of the ocean diminishes the heat of summer and the cold of winter. Examples are the small islands in the Pacific with an annual variation of temperature of about 5° or 6° F. (in the Friendly Islands the range is only 2°), and Great Britain and Australia with a range of 20° F.

2. *Continental, including extreme, climates*—those whose annual range of temperature is great because of distance from the sea. Examples are Canada (Quebec has a range of 58° F.), Central Russia (Moscow has a range of 49° F., from 64° to

[1] This subject is fully discussed in *Nature*, vol. xlix. p. 302, etc.

15°, while Edinburgh in the same latitude has a range of only 21° F., from 59° to 38°), and Central Asia (*e.g.* at Yakutsk the annual range is 102° F., from 62° F. in summer to −40° F. in winter).

The climate of the British Islands is peculiar in almost every respect, chiefly because of their insular position and the direction of the prevailing winds.

1. *The variableness of the weather* of these islands is due to their geographical position. It is the distribution of land and water that mainly determines the areas of high and low pressure, and as our islands are situated on the margin, as it were, with a great ocean to the west and the largest land surface of the globe to the east, the distribution of pressure over them is unstable, and they are subject to rapid and unexpected changes of weather.

2. *Rainfall.*—The peculiar distribution of rainfall has been already described on p. 103.

3. *The mean annual temperature* is remarkably mild and equable, the winters being much warmer and the summers cooler than other places in the same latitude. The mean annual temperature of the British Islands is about 48° F., decreasing with latitude from 53° in the Channel Islands to 45° in Shetland, while places on the west coasts are about 1° warmer than places in the same latitude in the east. The Registrar General's Reports show that the lowest death rate occurs when the temperature is between 50° and 60°, and as the temperature in our island for about six months of the year lies between these limits, and the average is not far below it, we are, so far as temperature is concerned, in the position of the most highly favoured nation.

Dr. H. R. Mill, in *The Realm of Nature*, p. 145, remarks that if it were not for the Gulf Stream, and especially the south-west winds, the January temperature would be 22° F. at London, 12°·5 F. at Edinburgh, and 7°·5 F. in Shetland, and the sea all round our islands would be frozen, whereas the actual temperatures during the coldest and hottest months of the year are—

	London. ° F.	Edinburgh. ° F.	Plymouth. ° F.	Shetland. ° F.
January	39·0	38·0	43·0	39·5
July	64·0	59·5	62·5	53·5
Range	25·0	21·5	19·5	14·0

In summer the hottest part of England is the Thames Valley in the vicinity of London, which has an average July temperature of 64° F.

4. *Winds and Storms.*—The United Kingdom is very

subject to the visitations of cyclones. They are common in July, and help to somewhat spoil the British summer. They are also common in November and December, and account for the mild, wet, windy weather of those months. Contrary to the general opinion, there are no equinoctial gales, for records of cyclones show that they are not more common at the equinoxes than other seasons.

In this country the most prevalent wind throughout the year is the south-west, the next is the west; and the north-east is the least prevalent. East winds are very common in spring (especially in April and May) and autumn, and in a less degree in November. At these times North Europe is a region of high pressure—that is to say, an anticyclonic region—and our dry parching east winds are simply a part of the outflow from these regions.

Questions.

1. What are the chief instruments employed at a meteorological station, and what is the nature of the observations made with each of them?
2. What are the principal causes which are taken into account by meteorologists in forecasting weather?
3. (*a*) Describe the cyclonic movements of the atmosphere.
   (*b*) Describe anticyclonic movements of the atmosphere.
   (*c*) What is the direction of these two kinds of movements in the northern and southern hemispheres respectively?
   (*d*) How does the study of these movements enable forecasts of the weather to be made?
4. State and explain the laws that govern climate. Define "isotherm." What data are required for drawing isotherms upon a map? Why do isotherms vary from parallels of latitude?
5. What facts have to be determined before the climate of a place can be known?
6. Explain fully the influence of forests on climate.
7. Explain the nature and cause of the difference between continental and insular climates.
8. Describe the general characteristics of the climate of England.
9. What are the chief peculiarities in the climate of the British Isles, and to what causes are these peculiarities to be ascribed?
10. Explain the causes of the difference of climate on the east and west coasts of Great Britain.
11. State what you know concerning the differences in climate and rainfall in the following places, and the causes of those differences: (*a*) Birmingham; (*b*) Penzance; (*c*) Yarmouth; (*d*) the Shetland Islands.
12. Describe some districts in the British Isles (*a*) where the rainfall is small, (*b*) where the rainfall is large. Explain the causes of the differences.
13. Compare the climate of London with that of New York and of Moscow, giving the reasons for the differences.

14. Describe the differences in the climate of the east coast of Labrador and the west coast of Ireland, and state the chief causes to which these differences are due.

15. Give an example (and in each case describe briefly the causes to which the peculiar climatal features are due) of—

(*a*) A district in which the rainfall is abnormally high.

(*b*) A district with no rainfall.

(*c*) A district in which the mean annual temperature is much higher than that of other places in the same latitude.

(*d*) A district in which the mean annual temperature is far below that of places in corresponding latitudes.

CHAPTER X.

TERRESTRIAL MAGNETISM.

The chief magnetic phenomena of the earth were described in the elementary work, pp. 129–134, and we have now merely to briefly supplement what has there been stated.

The Magnetic Elements of a Place.

1. *The angle between the geographical and magnetic meridians of a place is called the magnetic declination, or the variation of the needle at that place.* It is said to be east or west, according as the N.-seeking pole of the needle points to the east or west of the geographical meridian.

2. *The magnetic inclination, or dip, at a place is the angle which a magnetic needle, balanced on a horizontal axis so as to be free to move in a vertical plane, makes with the horizontal when the needle is placed in the magnetic meridian.*

3. *The magnetic intensity at a place is the force with which the earth's magnetism urges a magnetic pole of unit strength at the place.*

Nos. 1 and 2 tell us the *direction* of the earth's magnetic force, and No. 3 tells us its amount; and if we know these three we know everything about the earth's magnetism at the place, and hence they are called *the magnetic elements* of the place.

The essential instruments, therefore, of a magnetic observatory are: (1) a declinometer, to measure the declination; (2) an inclinometer, or dip circle, to measure the inclination or dip; and (3) a horizontal force magnetometer, to measure the intensity.

Description of the Declinometer, and its Use.—(*a*) In the declinometer there is a shallow, horizontal, circular tray of brass, AB (Fig. 66), over the centre of which is delicately poised a compass needle, C. (*b*) AB is supported by an upright pillar, P, on which it can rotate as an axis, the amount of rotation being measured by the fixed graduated horizontal circle DE. (*c*) Two uprights, F and G, are fitted to opposite

sides of AB, and on the top of the uprights rests a horizontal axis supporting a telescope, T. (*d*) T is fixed rigidly at right angles to the horizontal axis (the centre of which is right over the centre of the needle) so that it can only turn in a vertical plane, but by rotating AB the telescope can be moved in a horizontal plane.

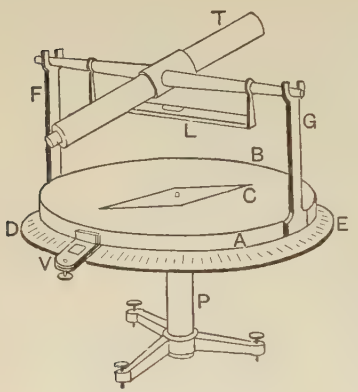


FIG. 66.—The declinometer.

To ascertain the Declination or Variation.—(*a*) Carefully level the instrument by means of the three levelling-screws, till the bubble in the spirit-level L is at the centre.

(*b*) To get the geographical meridian, if this has not already been done, point the telescope to the sun at noon, and note the reading of the vernier V which moves along with AB. Or at night point the telescope to some star whose time of transit (see p. 255) is given in the Nautical Almanac; we know from this how many degrees the axis of T makes with the geographical meridian, and by turning round AB this number of degrees on the horizontal graduated circle DE we would bring the axis of the telescope into the geographical meridian. Then, as in the former case, note the reading of the vernier V.

(*c*) Next AB is turned round and the telescope tilted till the marked end of the needle C is viewed. The axis of the telescope must then be in the magnetic meridian. The reading of V is again noted. The difference between this reading and the last will be the declination.

Description of the Dip Circle, and its Use.—(*a*) There is a horizontal plate AB (Fig. 67), which is supported by an upright pillar, P, on which it can rotate as an axis, the amount of rotation being measured by the fixed graduated horizontal circle DE. (*b*) On AB there is fixed a framework which supports the vertical graduated circle F, at the centre of which is placed the dipping-needle C, whose axis of suspension, in good instruments, moves in agate supports to diminish the friction.

To ascertain the Inclination or Dip.—(*a*) The instrument is carefully levelled by means of the three levelling-screws

till the bubble is at the centre of the spirit level, L. (*b*) To bring the needle into the magnetic meridian, the most convenient way is to turn AB till the needle is standing vertically. The plane of the needle is then at right angles to the magnetic meridian, so that by now turning AB through 90° on the horizontal graduated circle DE, we bring the plane of the needle into the magnetic meridian. (*c*) Note the number of degrees on the vertical graduated circle F to which either the lower or upper end of the needle is pointing: this is the dip.

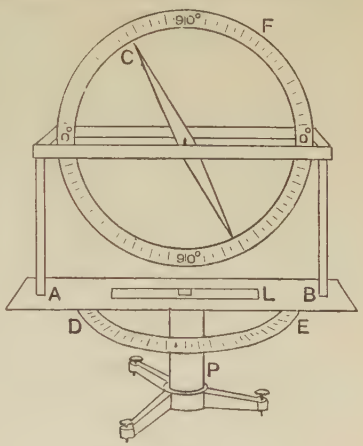


FIG. 67.—The dip circle.

The Total Magnetic Intensity at any Place, and its Horizontal and Vertical Components.—In the *Elementary Physiography*, p. 17, we described how, by the parallelogram of forces, a force may be resolved into two components in any two given directions. The earth's total magnetic intensity at a place acts along the direction in which the dipping-needle sets itself when in the magnetic meridian. Suppose the earth's total intensity at a place to be represented in direction and magnitude by the line AB (Fig. 68), then if we draw the horizontal line AC, and drop the perpendicular BC upon it, and complete the parallelogram ACBD, the angle marked *i* will represent the dip, and AC and AD will represent respectively the horizontal and vertical components of the earth's total magnetic intensity at the place. But in a right-angled triangle the ratio of the base to the hypotenuse is called the "cosine" of the angle between them; therefore—

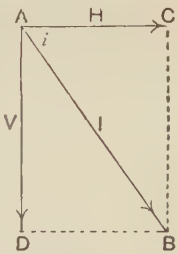


FIG. 68.—The earth's magnetic intensity, I, at any place may be resolved into a horizontal component, H, and a vertical component, V.

$$\frac{AC}{AB} = \text{cosine CAB}$$

$$\text{that is, } \frac{H}{I} = \text{cosine } i$$

$$\therefore I = H \div \text{cosine } i.$$

The total magnetic intensity, I, at any place is not observed directly; it is calculated from the measurement of the horizontal component H and the dip *i*. H can be determined by means of a horizontal-force magnetometer, and the method of doing so is explained in text-books on Magnetism; and the dip *i*

is found in the manner described in the last paragraph; and then, by dividing the horizontal component by the cosine of the dip (the numerical value of the cosine of any given angle can be found from tables), we obtain the magnetic intensity at the place.

EXAMPLES OF THE MAGNETIC ELEMENTS AT DIFFERENT PLACES.

Date.	Place.	Declination. Westerly.	Inclination.	Horizontal Force in C.G.S. Units.
		° ′	° ′	
1896	Greenwich	16 56·5	67 10·0	1·8367
1897	,,	16 50·4	67 7·1	1·8387
1898	,,	16 39·2	67 11·8	1·8387
1899	,,	16 34·2	67 10·2	1·8419
1889	Paris	15 44·6	65 12·6	0·19522
1890	,,	15 38·7	65 11·0	0·19543
1891	,,	15 32·8	65 10·1	0·19558
1890	Washington	4 5·8	71 4·5	0·19860
1891	,,	4 9·7	71 5·1	0·19855
1892	,,	4 14·2	71 3·9	0·19849
1892	Toronto	4 29·2	74 37·2	0·16623
1893	,,	4 36·4	74 36·2	0·16635
1894	,,	4 42·3	74 34·7	0·16633

The Distribution of the Earth's Magnetism.—For purposes of convenience such data as those in the above

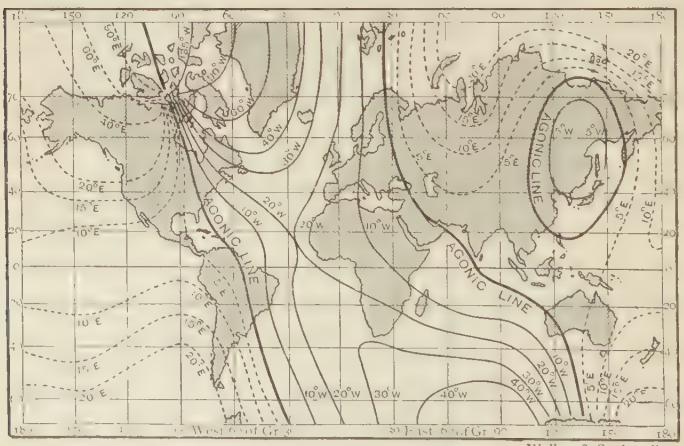


FIG. 69.—Isogonic lines for the year 1900.

table are given by means of magnetic maps. But a map with the magnetic elements of all the places stated in numbers would be almost illegible because of the mass of figures all of which would occur over and over again. Hence it is much better to draw a line passing through all places having the same declination, and only put the number once on the line. And similarly for dip and intensity. *Lines drawn on a map through*

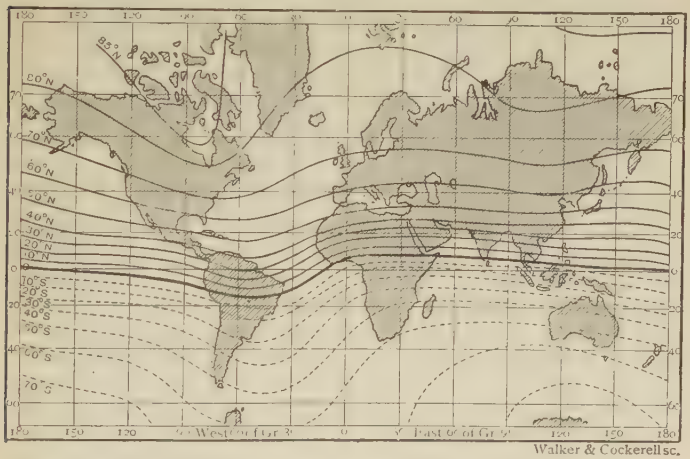


FIG. 70.—Isoclinic lines for the year 1900.

places having at a certain period (*or epoch as it is sometimes called*) *the same declination, are called isogonic lines* (Gr. *isos*, "equal;" *gonia*, "angle"). Similar lines for dip are called *isoclinic lines* (Gr. *isos*, "equal;" *klino*, "I incline"), and for intensity *isodynamic lines* (Gr. *isos*, "equal;" *dynamis*, "force"). Owing to the irregularities of the distribution of the earth's magnetism, the forms of those lines are by no means simple, as a glance at Figs. 69 and 70 will show. In Fig. 69 the isogonals for the year 1900 are drawn, the whole lines indicating westerly declination, and the dotted ones easterly declination. The heavy isogonic lines pass through places in which the compass needle points to the true north, that is, where the declination is zero; and hence these lines are called *agonic lines* (Gr. *a*, "without;" *gonia*, "angle").

There are two distinct agonic lines. One is oval-shaped, and lies mostly in Eastern Siberia. The other goes right round the earth. Starting from

the magnetic north pole, it passes through Hudson Bay, down through North America, cuts the equator in longitude 56° W., passes down through Brazil and into the Antarctic Ocean to the magnetic south pole. It reappears on the other side, and passes through the western corner of Australia, cuts the equator at 80° E. longitude, passes through the Persian Gulf, North Cape, and thence to the magnetic north pole.

The thick line marked 0° in Fig. 70 is the line of zero dip, also called the *magnetic equator*, or *aclinic line*. The inclination rapidly increases on both sides of the magnetic equator, the N.-seeking pole of the needle dipping in the northern hemisphere, and the S.-seeking end in the southern. It will be seen that the magnetic equator never departs very far from the geographical equator. It cuts the latter in the Atlantic about longitude 10° W., and if followed eastwards from this point, it rises till it reaches the centre of Africa, and then more slowly descends and cuts the equator again in the centre of the Pacific about longitude 170° W. From this point it very gradually descends southwards till it reaches the centre of South America, and then rises again to the point from which we traced it.

Position of the Earth's Magnetic Poles.—The earth's magnetic poles are the regions in which the earth's magnetic force acts wholly vertically and has no horizontal component. We might therefore define the magnetic poles of the earth as *the places at which the dip is* 90°, *and therefore the horizontal component zero*. They are also sometimes called the *Poles of Verticity*. The north magnetic pole is at Boothia Felix (lat. 70° 5′ N., and long. 96° 46′ W.), about 1400 miles from the north geographical pole. The south magnetic pole has not yet been reached, but it is probably near lat. 75° S., and long. 150° E.

At the magnetic poles a dipping-needle points vertically downwards, whereas an ordinary horizontal magnetic needle remains in any direction in which we place it, because the earth's magnetism has no horizontal force there.

At the magnetic equator neither end of a dipping-needle inclines downwards, that is to say, the needle takes up a horizontal position ; a compass needle at the magnetic equator points in the magnetic meridian as usual.

The Poles of Intensity, or the Magnetic Foci.—The magnetic force of the earth is not, as might be expected, a maximum at the magnetic poles or poles of verticity. There are two places of maximum intensity in the northern hemisphere and two in the southern. These are called the poles of intensity, or the magnetic foci of the earth. One northern focus is in North America to the south-west of Hudson Bay ; the other is weaker than this, and is in North Siberia. The southern foci are also of unequal strength.

We may summarize the positions of the poles of verticity and poles of intensity thus—

	Latitude.	Longitude.
North magnetic pole . . .	70° 5′ N. .	96° 46′ W.
South ,, ,, . . .	75° S. .	150° E. (approximately)
North focus (the stronger) .	52° N. .	90° W.
,, ,, (the weaker) .	70° N. .	115° E.
South ,, (the stronger) .	65° S. .	140° E.
,, ,, (the weaker) .	50° S. .	130° E.

Variations of the Earth's Magnetism.—The magnetic elements not only vary from place to place, but the table on p. 146 shows that they also vary for the same place at different times. The variations are of two classes: some are regular, and either take place from age to age, or year to year, or day to day, and are therefore called respectively secular, annual, or diurnal; others are irregular, and are called magnetic storms.

Secular Variations.—The declination at London in 1576 was 11° E. This gradually diminished till 1660, when it was zero. The change still continued until in 1810 the maximum value of $24\frac{1}{2}$° W. was reached. Since then the declination has been changing the other way, being only 16° 34′·2 W. at London in 1899, the rate of decrease being about 6′ per annum. These changes are represented graphically in Fig. 71.

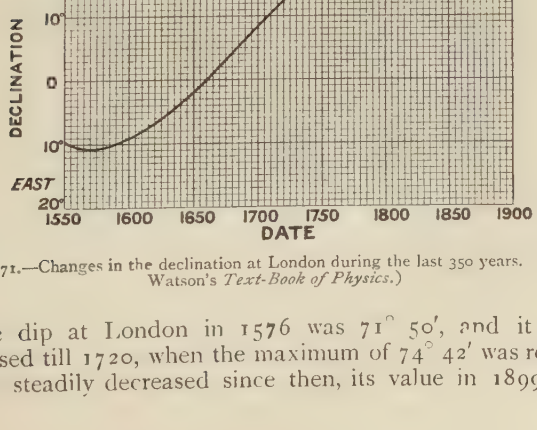


Fig. 71.—Changes in the declination at London during the last 350 years. (From Watson's *Text-Book of Physics.*)

The dip at London in 1576 was 71° 50′, and it slowly increased till 1720, when the maximum of 74° 42′ was reached. It has steadily decreased since then, its value in 1899 being

67° 10′·2, and the present rate of decrease about 1′·6 per annum.

The intensity is subject to a similar slow change, and at other places the magnetic elements are undergoing like secular variations, although not, of course, at the same rate. At one time it was believed that the changes were due to the magnetic poles shifting their positions, but recent investigations rather point to slow geological changes in the earth's crust as the probable cause.

Annual Variations.—There are also changes corresponding in period with the revolution of the earth round the sun. In this country the westerly declination varies about 16′ during the year, being greatest at the vernal equinox, diminishes from this time till the summer solstice, and during the next nine months slowly increases to the maximum again. The dip varies in Great Britain 0′·54 during the year, being below its mean value from April to September, and above it during the remainder of the year.

Diurnal Variations.—The magnetic elements also vary hour by hour, the range of their daily variation depending on

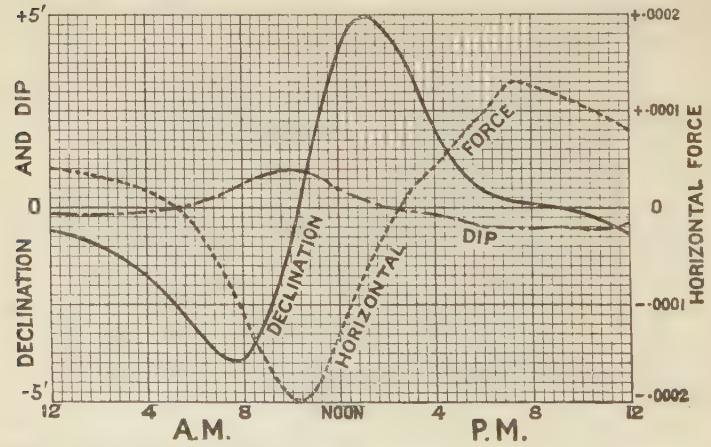


FIG. 72.—Range of the diurnal variations in the magnetic elements at Kew Observatory during a day in summer. (From Watson's *Text-Book of Physics.*)

the time of the year and the position of the place. The curves in Fig. 72 give the change in each of the three elements at Kew during a day in summer. The horizontal line marked o

represents the mean value in each case. We see from the diagram that the declination is at its mean value about 10 a.m. From that time it slowly increases, and about 1 p.m. (the hottest part of the day) it reaches a maximum of about 5′ to the west of the mean position. The declination then commences to decrease until the mean is regained about 10 p.m. It continues to decrease till 8 a.m., when it is about 4′ to the east of the mean value. The diurnal range in declination is thus about 9′ or 10′. The dip also undergoes a daily change, reaching its maximum value about 10 a.m., and its minimum about 6 p.m., the total range being about 2′.

Irregular Variations, or Magnetic Storms.—In addition to the regular, progressive changes we have just described, there occur sudden, irregular disturbances of much greater extent in all the three magnetic elements over an extensive area of the earth. These are called magnetic storms, the general nature of which will be understood from Fig. 73. While such a storm is raging, compass needles may

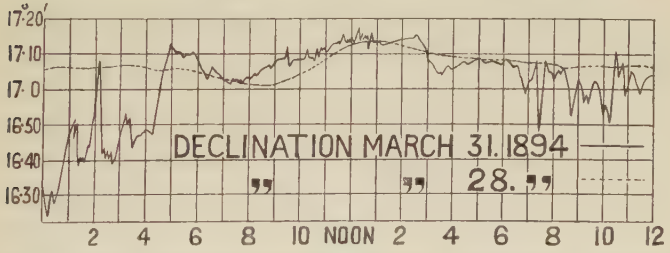


FIG. 73.—The irregular disturbance of declination during a magnetic storm. The dotted curve shows the diurnal change in declination at Greenwich Observatory during an ordinary quiet day, and the zigzag curve is a copy of the photographic trace of the declination-magnetograph during a magnetic storm. (From Watson's *Text-Book of Physics*.)

swing irregularly from side to side through 2° or more, and a photographic record of the movement, instead of being smooth, is a series of lawless zigzags.

The cause of these magnetic storms is obscure in the highest degree. They are intimately connected with auroras, for magnetic storms are generally, although not universally, accompanied by auroral displays, even in latitudes where auroras are not common. Conversely, no great display of the aurora takes place without contemporaneous magnetic disturbances. Moreover, both sets of phenomena – magnetic storms and

auroras—are certainly related in some way with sun-spots, although the nature of the connection has yet to be explained. Periods of maximum number of sun-spots recur, as we shall see later on, about every eleven years, and at these times magnetic storms and auroras are most frequent. Until recently it was commonly asserted that no great spot breaks out on the sun without being accompanied by a magnetic storm on the earth. But this is not the case, for in only a few instances have solar and magnetic disturbances occurred together; great sun-spots often occur without corresponding magnetic storms, and sometimes two or more such storms may occur even in the course of a day without corresponding disturbances on the sun's surface being recorded. We are not, therefore, warranted in asserting that the sun has an immediate magnetic influence upon the earth, and the precise cause of magnetic storms is still unknown.

Questions.

1. Define the magnetic elements, and state how they are determined at any place.
2. State the magnetic elements, and describe how two of them are obtained.
3. What instruments are used in a magnetic observatory? State the objects of the employment of each.
4. State what you know of the earth's magnetic poles and equator.
5. State what you know concerning the distribution of the earth's magnetism.
6. Name the elements of the earth's magnetism. How would you locate the positions of the magnetic poles?
7. Describe roughly the positions of the earth's magnetic poles, and state how (*a*) a dip needle, (*b*) a compass needle would behave if placed at a magnetic pole.
8. What facts relating to terrestrial magnetism are given in a magnetic chart of the earth's surface?
9. Why is it necessary for the captain of a ship to take with him charts showing the magnetic declination for the parts of the world in which he travels?
10. Describe briefly the daily and yearly changes of magnetic declination and dip in Great Britain.
11. State what you know about the secular change of magnetic declination at London for the past two or three hundred years.
12. From Fig. 71 tell approximately (*a*) what the declination at London was in the year 1870; and (*b*) in what years its value was 19° W.
13. What connection has been observed between sun-spots, auroras, and magnetic storms?
14. State what you know concerning the connection between the aurora and magnetic storms.

CHAPTER XI.

LAKES AND SEAS.

Classification and Modes of Origin of Lakes.—No perfectly satisfactory classification of lakes has as yet been given, for the reason that, in some instances, the manner in which they have originated is doubtful. We shall, in the main, follow the classification given by Professor James Geikie, F.R.S.[1]

Lakes are of two great classes : I. Fresh-water lakes ; II. Salt-water lakes. Lakes having outlets almost invariably contain fresh water, while those without outlets contain saline, undrinkable water. We may further subdivide them according to their mode of formation, as follows :—

I. Fresh-water Lakes.

1. *Obstruction Lakes.*—A glacier or a sheet of lava advancing across a valley, or rock-masses falling in a landslip, may obstruct the drainage of a valley, and so give rise to a lake. The obstruction may be only temporary, and may yield to the pressure of the water and occasion destructive flooding. The famous "Parallel Roads" of Glen Roy, in Invernesshire, are the beaches of an ice-barrier lake.

2. *Crater Lakes.*—These are generally of small size, and occupy the craters of extinct or dormant volcanoes. A good example is the picturesque Lake Albano near Rome. It is six miles in circumference. Lake Averno and some others in Central Italy have been similarly formed.

3. *Earth-movement Lakes.*—Wrinkling of the earth's crust by contraction may occasionally cause hollows in which water collects. The great African lakes have probably been formed in this way. Also elevations due to wrinkling may obstruct the lower end of a valley and so give rise to a lake.

4. *Glacial Lakes.*—These consist of—

(*a*) *Rock-Tarns*, which are small lakes occupying hollows in

[1] *Outlines of Geology* (Stanford), pp. 43-47.

ice-worn platforms, generally on the sides of mountains or the tops of ridges. They are very numerous in all parts of the Scottish Highlands, are irregularly scattered, having no connection with the lines of valleys, and are generally believed to be due to the scooping-out action of the thick sheet of ice that covered the region during the glacial period. An excellent example is Loch Coruisk, in Skye.

Similar lakes, but on a larger scale, and called rock-basins, occur in rocky depressions in glens (hence sometimes called *glen-lakes*) in Cumberland, Westmoreland, Wales, Scotland, and Killarney. Their origin is still disputed. As there are unmistakable traces of glacial action in the glens in which they occur, they have been attributed by Sir A. C. Ramsay and others to the erosive action of the glacier that occupied the glen. But many doubt whether glaciers can scoop out hollows in solid rocks, and point to the absence of such lakes in the glacier regions of the Himalayas, etc., and say it is much more probable that the rock-basins existed before the glacial period, and all that the ice did was to smooth and striate the valleys, or that in some cases the hollows may have been formed by wrinkling of the earth's crust while still covered by the sheet of ice.

(*b*) *Moraine-Tarns* are small lakes formed by a glacier gradually retreating up its valley owing to a warmer climate supervening in the region. Then the heap of stones and *débris* forming the terminal moraine dams up the valley, so that the water from the melting ice forms a lake. Small tarns of this kind may be counted by hundreds at the heads of the glens or the mouths of corries in the Highlands of Scotland, *e.g.* Loch Avon at the foot of Ben Macdhui and Cairn Gorm, and the dark loch on the northern slopes of Lochnagar, etc.

II. Salt Lakes may be divided into two classes—

1. Those which owe their saltness to the evaporation of their pure water, and the consequent concentration of the salts brought in solution by their feeders. They may be defined as lakes which have no outlet to the sea. They almost all occur in regions having a mean annual rainfall of less than 10 inches, and hence, the supply of drainage water being small and intermittent, the streams make little progress in cutting through the lake-forming obstructions. The lakes are constantly losing pure water by evaporation, and the dissolved salts are left behind, making the water more salt and bitter until it becomes supersaturated with them, and they are

deposited in layers at the bottom and round the margin. The Dead Sea (salinity 24 per cent.) is an excellent example. Lakes of this class occur abundantly scattered over the drainage areas in the hearts of continents, as in Central Asia, and the Great Salt Lake of Utah, etc., in North America.

2. Those which originally formed part of the ocean, but have been cut off from it by some means or other, such as the elevation of the intervening region. Thus isolated, they are exposed to more evaporation than is made up for by inflowing rivers, and they have therefore shrunk in extent, and sometimes become salter than the parent ocean. Salt lakes of this class range in size from mere pools and lagoons to great inland seas like the Caspian Sea and Sea of Aral. The Caspian Sea is by far the largest lake in the world, having an area of 180,000 square miles (more than five times that of Lake Superior, which comes next), and a maximum depth of from 2500 to 3000 feet. Sir A. Geikie says of it[1]—

"The shells in it are chiefly those still living in the Black Sea. Banks of them may be traced between the two seas, with salt lakes and marshes and other evidence to prove not only that the Caspian was once joined to the Mediterranean, but that a great firth ran up between Europe and Asia, and probably stretched completely across what are now the steppes and plains of the Tundras, till it merged into the Arctic Ocean in the direction of the Gulf of Obi. At present the amount of water carried in by rivers just balances that removed by evaporation, so that the level appears to be no longer sinking. Owing to the enormous volume of fresh water poured into it by the Volga and other rivers, the Caspian is not as a whole as salt as the main ocean, and still less so than the Mediterranean, yet we see the inevitable result of evaporation in the deposition of salt continually taking place in the shallow pools on its borders."

The Functions of Lakes.

1. *Regulating the flow of rivers*, and thus keeping up the supply in times of drought, and preventing or lessening the destructive effects of floods. Floods in tributary streams upon entering a lake are spread over such a large area that they do not materially raise the level of the surface of the lake, and therefore the effect on the outflowing river is not great.

2. *Filtering river water, and so forming new deposits* which gradually cover the whole area of the lake. When rivers enter lakes their waters spread out and move much more slowly. They are thus compelled to part with their sediment, and, where they enter the lake, form deposits of gravel, sand, silt, mud, and

[1] *Encyclopædia Brit.*, vol. x. p. 279.

organic matter, which gradually extend into the lakes and fill them up, converting them into rich alluvial plains or lake-lands.

Effect of Winds on the Sea—Waves.—In connection with the elementary stage of this science we described how winds blowing continuously in one direction cause currents. Another effect is that winds, by their friction on the surface of the water, produce waves; for wind striking the surface of the water obliquely depresses it, and thereby ridges up the neighbouring parts of the water and causes a wave, the *form* of which advances as a line of rollers before the wind. The individual particles composing the wave at any moment merely move up and down, as is shown by the movements of objects floating on the surface. But when waves from the open sea reach water so shallow that the wave-motion reaches to the bottom, then the lower part of the wave is retarded by friction, and the parts behind overtake it. The wave thus becomes higher, until finally the crest topples over in a graceful curve, and rushes upon the beach amidst foam and spray, the roller having become a *breaker*.

The Size and Speed of Waves in the Open Ocean.—The *height* of a wave is the vertical distance from trough to crest, and the *length* of a wave (sometimes also called the *breadth*) is the distance from crest to crest. These dimensions and the velocity of the wave in the open ocean depend upon the force and continuance of the wind. The largest waves are between 50 and 60 feet high, half a mile long, and rush along at the rate of 80 miles an hour. Ordinary storm-waves are not more than 30 feet high, and 600 feet long, and travel about 37 miles an hour. In the shallow North Sea the highest waves probably never exceed 15 or 20 feet.

The Depth of Water affected by Waves.—The commotion is confined to a comparatively thin layer, for the motion rapidly decreases with distance from the surface. It is probable that ordinary waves produce no disturbance at a depth of 20 fathoms, and even when the greatest waves are passing along the surface it is unlikely that the motion penetrates as far as 500 fathoms.

The Tides.—A visit of one day to the seashore is sufficient to show the alternate rise and fall of the surface of the sea. A rocky shore or sandy beach bare in the morning is covered by the sea in the afternoon. For about six hours the sea slowly rises, and then falls for the same length of time. This regular rise and fall of the waters of the ocean twice a day are called

the tides. As the sea rises it floods the low-lying parts along the coast, and hence the rising tide is called *flood tide;* when the level of the water is highest we have *high tide.* As the water recedes, or ebbs away from the submerged flats, we have *ebb tide;* and when it has reached its lowest point we have *low tide.*

Tidal phenomena are somewhat complicated, and, whenever it is possible, the only satisfactory way of becoming acquainted with them is by direct observation. Let us mention some of the facts that a careful observer might learn in the course of a month or more at the sea-coast:—

1. High water occurs about every 12 hours.
2. If the position of the moon be also noted, it is found that high water occurs about the time the moon is crossing the meridian of the place, or is on the opposite side of the earth from it.[1]
3. The height of high water varies from day to day, and there are two maxima and two minima high tides in about 27 days.
4. The two maxima correspond very nearly with new and full moon, and the minima with half-moon.
5. The interval between two successive high waters always exceeds 12 hours.
6. The amount of this excess is about 26 minutes, but it varies; it goes on increasing for about a week, then it diminishes for about a week, then it increases again, and so on.
7. If the moon's phases be also noted, it is found that the increase referred to takes place before new and full moon, and the decrease after new and full moon.

The remainder of this chapter will be devoted to an explanation of the above peculiarities.

How the Moon causes Tides.—We must look to the Law of Gravitation for the explanation of tides. To simplify the following explanation, let us imagine the earth to be a solid sphere completely covered with an ocean of uniform depth. Now, the distance ME of the moon from the centre of the earth is 240,000 miles, or 60 times the earth's radius (4000 miles), so that in Fig. 74 MA is 59 terrestrial radii. But

[1] Even the Greeks and Romans, with their meagre opportunities of observation in the Mediterranean, knew in a general way the connection between the tides and the position of the moon. Julius Cæsar, referring to his landing in Britain, says, "That night it happened to be full moon, which time is accustomed to give the risings of water in the ocean." And Strabo, an ancient Greek writer, says, "Soon after moonrise the sea begins to swell up and flow over the earth till the moon reaches mid-heaven. As she descends thence the sea recedes till about moonset, when the water is lowest. It then rises again as the moon, below the horizon, sinks to mid-heaven under the earth."

gravitational attraction is inversely proportional to the square of the distance; hence the moon's attraction for the water at A is greater than its attraction for the solid earth in the ratio of the square of 60 to the square of 59, and this difference of attraction causes the water to be heaped up at A directly under the moon, so that there is high tide there.

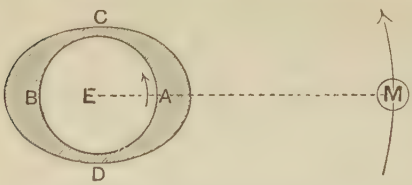


FIG. 74.—The tide-raising action of the moon. M represents the moon, and E the earth. It is scarcely necessary to say that the relative sizes and distances are not drawn to scale.

Again, the moon's attraction for the solid earth is greater than its attraction for the water at B in the ratio of 61^2 to 60^2, and the earth, being more strongly attracted, is pulled away, as it were, and leaves the water heaped up at B, so that there is also high tide on the opposite side of the earth from the moon. As a consequence of the piling up of the water at A and B, it is drawn away from C and D, and there is low tide at those places.

Of course, the solid earth and the waters are not separated from each other at A and B. There is merely a slight tidal bulge of the waters at these places towards and away from the moon, and the earth turning on its axis from west to east makes this watery bulge appear to travel from east to west. If the moon were stationary, every place on the earth would have two high and two low tides every 24 hours, but as the moon revolves round the earth in the same direction as the earth rotates, the average interval between two successive transits of the moon over a certain meridian is about 24 hours 51 minutes (see p. 344), and this is consequently the period in which there are two high tides at a place. Fig 75 shows this.

It is to be hoped that it has been made sufficiently clear in the foregoing explanation that it is not the attraction of the moon for the earth or the waters covering it that causes the tides, but that the tide at A is due to the *difference* of the moon's attraction on the waters at A and on the solid earth. Similarly for the tides at B.

The above is the theory of the tides as worked out by Newton, and while it furnishes a simple general explanation of the chief tidal phenomena, it only gives an approximation to the actual conditions at any place, for the earth is not completely enveloped by water, the oceans are not of uniform depth, and they are interrupted by continents with very irregular outlines.

Tides raised by the Sun—Comparison of the Tide-generating Forces of the Sun and Moon.—An exactly similar train of reasoning applies to the difference of the sun's attraction for the solid earth and the waters covering it, so that there are solar as well as lunar tides, and if tides depended on the magnitude of the attraction of the tide-producing body, then the solar tides would be almost 200 times the height of the lunar ones, for the sun attracts the earth with nearly 200 times the force that the moon does. But, as we have said, tides are due to the differential attraction of the tide-raising body for the earth and the waters, and from the following explanation it will be seen that for the moon this difference is more than double that for the sun:—

The sun's mass is = 332,000 times earth's mass
The moon's ,, = $\frac{1}{81}$ or 0·0123 of ,,
The sun's distance is = 93,000,000 miles, or 23,250 times earth's radius
The moon's ,, = 240,000 ,, 60 ,, ,,

Now, by the law of gravitation, the attraction is directly proportional to the mass, and inversely proportional to the square of the distance, therefore the moon's attraction on the earth is proportional to $\frac{0{\cdot}0123}{60^2}$, and its attraction on the water at A is proportional to $\frac{0{\cdot}0123}{59^2}$. Hence the difference of the moon's attraction on the water at A and on the earth is proportional to—

$$\frac{0{\cdot}0123}{59^2} - \frac{0{\cdot}0123}{60^2}.$$

Similarly, the sun's tide-raising force at A is proportional to—

$$\frac{332000}{23249^2} - \frac{332000}{23250^2}.$$

Therefore—

$$\frac{\text{Lunar tide at A}}{\text{Solar tide at A}} = \frac{\frac{0{\cdot}0123}{59^2} - \frac{0{\cdot}0123}{60^2}}{\frac{332000}{23249^2} - \frac{332000}{23250^2}} = \frac{5}{2} \text{ approximately.}$$

In like manner—

$$\frac{\text{Lunar tide at B}}{\text{Solar tide at B}} = \frac{\frac{0{\cdot}0123}{60^2} - \frac{0{\cdot}0123}{61^2}}{\frac{332000}{23250^2} - \frac{332000}{23251^2}} = \frac{5}{2} \text{ approximately.}$$

That is to say, the tides due to the moon are about two and a half times as high as those due to the sun.

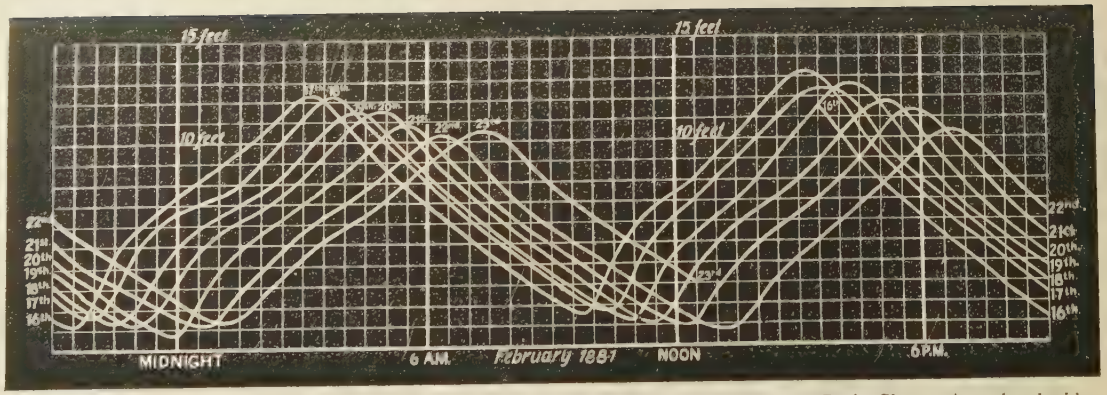


FIG. 75.—The seven daily curves traced during a week by a tide-gauge at the entrance to Queen's Dock, Glasgow (reproduced with Lord Kelvin's permission). This instructive diagram shows that there are two high tides a day; that high tide one day is about 51 minutes later than on the preceding day; that the two high tides in a day are not the same height (for the tide will be higher when a place is towards the moon than when on the opposite side of the earth from it); and that the level of the water at high tide varies on successive days (according to the relative position of the moon and sun).

Lunar and Solar Tides combined — Periodical Variations in the Tides.—The sun and moon both cause tides, and what we observe at any instant is the resultant of their combined tide-raising forces. The height and period of this resultant tide are continually varying for several reasons, of which we shall only give two :—

(1) *Spring and Neap Tides.*—At new or full moon the sun and moon act together in causing high tide at A and B (Fig. 76) and low tide at C and D. Hence at these periods of the

FIG. 76.—Spring tide at new or full moon. At these times the range of the tide is greatest.

month there occur the highest high tides and lowest low tides. These very high tides are called *spring* tides, that is, high-rising

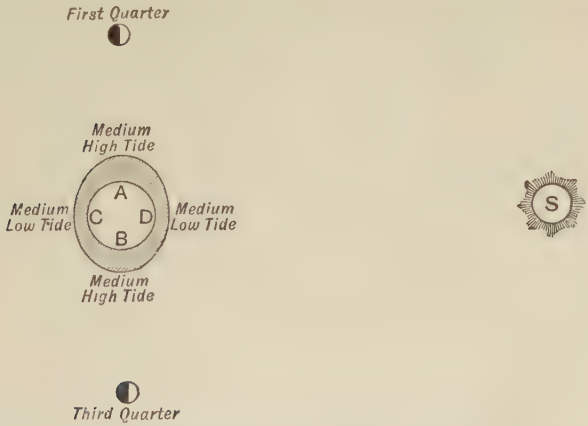


FIG. 77.—Neap tide when the moon is in its first or third quarter. At these times the range of the tide is least.

tides, having nothing to do, of course, with the season of spring.

For a week after new or full moon the water at each

successive tide rises to a somewhat less height and falls to a somewhat less depth until the moon's phase is the first or third quarter. Then the moon and sun are acting at cross purposes, for while the moon causes high tide at A and B (Fig. 77), the sun causes low tide at the same places. Hence twice a month the tides are lower than usual, and are called *neap* tides, that is, *nipped* or scanty tides. At the same periods the moon causes low tides at C and D, but they are not so low as usual, because the sun is causing high tide at the same places.

From what we have said it will be seen that a spring tide is the sum of a lunar and solar tide, and a neap tide is the excess of a lunar over a solar tide, so that since lunar tides are to solar tides as 5 to 2, spring tides are to neap tides as $5 + 2$ is to $5 - 2$, that is as 7 to 3.

(2) *Priming and Lagging of the Tides.*—Another effect of the combined influence of the sun and moon is to cause the interval between successive high tides to vary somewhat. At new or

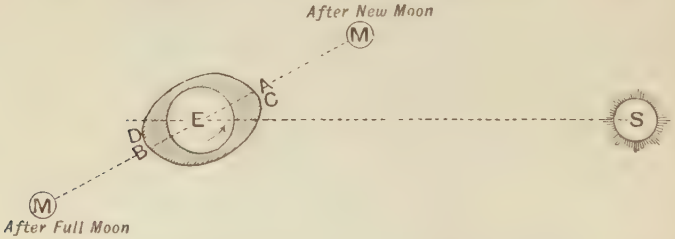


FIG. 78.—To explain the priming of the tides after new and full moon.

full moon the tidal wave is directly under the moon. But after new moon the resultant tidal waves are not directly under and away from the moon, but a little behind it (Fig. 78), because of

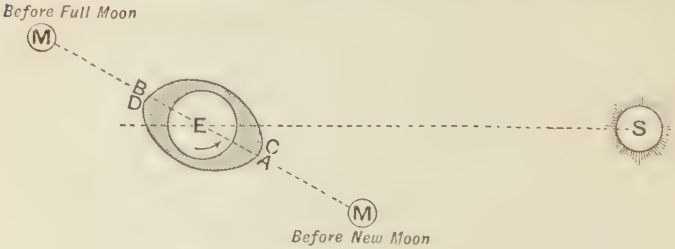


FIG. 79.—To explain the lagging of the tides before new and full moon.

the influence of the sun. Instead of being at A and B, they are at C and D. Hence as the earth rotates in the direction indicated by the arrow, high tide arrives a little sooner than it would if the moon alone were acting, and this is called "priming" or acceleration of the tide. Exactly the same thing occurs after full moon.

Similarly, before new moon the high tide is in a position intermediate between the direction of the moon and that of the sun, and hence as the earth rotates the tide arrives later at a place than it would if the moon were the sole agent: and this is called "lagging" or retardation of the tide (Fig. 79). The same thing occurs before full moon.

On account of priming or lagging, the tides on successive days may be accelerated or retarded as much as 13 minutes.

Establishment of a Port.—We have as yet explained tidal phenomena as they would be if the waters of the ocean at once responded to the attraction of the moon and sun, and if they covered the whole earth to a uniform depth. But these ideal conditions are far from being fulfilled. On account of the inertia of the water, the tide-producing forces require some time to start the tidal wave, which therefore usually crosses the meridian after the moon. Also the irregular configuration of the land, the unequal depths of the ocean in different localities, the action of prevailing winds, and many other causes restrict and hamper the movements of the waters. The consequence is that there generally is an interval of time between the moon's meridian passage and the time of next high water. This is different at different ports, but is practically a constant for any particular port, and is called *the establishment of the port*, which, therefore, may be defined as *the interval of time between the meridian passage of the moon and of the corresponding high tide at the port.* This can only be obtained at any particular place by observation, and is so valuable to navigators that its amount for all important ports is published in tables. For example, its value at Gibraltar is nearly zero, at London Bridge 2 hours, at Liverpool $11\frac{1}{2}$ hours, at New York $8\frac{1}{4}$ hours, and so on.

Co-Tidal Lines.—Tidal charts of the oceans have drawn upon them lines connecting those places which have high water at the same moment of Greenwich time. These are called co-tidal lines. They are shown for all the oceans in Fig. 50, p. 102, but considerable lengths of the lines are conjectural, as it is only along coasts and in the neighbourhood of islands

that observations can be made. We have, however, pretty accurate information of their position in the seas round the British Islands, and the reader should, therefore, carefully study Fig. 51, p. 104. The numbers on the co-tidal lines in these two maps indicate hours, and merely show the length of time taken by the tidal wave to pass from one part of the ocean to another.

Course of the Tidal Wave.—If the earth were entirely covered with water, the two opposite tidal waves would pass round the globe from east to west regularly in 24 h. 51 m., but the varying depth of the water and the obstruction offered by continents change both the direction and speed of the tides. It is only in the southern part of the Pacific Ocean and the adjacent Antarctic Ocean that there is a complete ring of water round the globe, and hence only here has the tidal wave room to form. The wave passes westwards across this region, and is deflected northwards from it into the other oceans.

By means of the co-tidal lines in Fig. 50 we can trace its course round the world. Twice a day the parent wave starts in the deep waters of the Pacific Ocean off Callao on the west coast of South America, and travels westwards at speeds varying with the depth of the ocean. The deeper the ocean the faster it travels. In about 12 hours it reaches New Zealand, passes Australia, and crosses the Indian Ocean, in which it combines with a small tide raised by the moon in that ocean. In about 30 hours it passes the Cape of Good Hope into the Atlantic, where it unites with (*a*) a direct tide raised off Africa and (*b*) a reversed tide, 24 hours younger than itself, which has moved round Cape Horn from the Pacific. The united wave then travels northwards in the Atlantic at the rate of about 700 miles an hour, and faster at the centre than at the sides, as is shown by the arched form of the co-tidal lines. The tide is about 40 hours old when it reaches Florida, and, owing to the direction of its advance, it arrives at all the eastern ports of the United States within 2 or 3 hours of that time. About the same time the wave reaches Ireland, and proceeds onward between Iceland and Scotland and travels eastward to Norway, and round North Cape into the Arctic Ocean.

The course of the tidal wave round the British Islands is peculiar (Fig. 51). It divides at the south-west of England, part going up the English Channel, and part up St. George's Channel, and in the neighbourhood of the Isle of Man this branch meets a part that has gone round the north coast of

Ireland. A branch of the wave that has proceeded round the north coast of Scotland passes southwards along our east coast, and reaches the mouth of the Thames about 60 hours after it left the South Pacific. At the Nore it combines with a branch that has passed up through the English Channel and is 12 hours younger than itself. The combined tide then proceeds eastwards to the other side of the North Sea, and travels from south to north along the Belgian, Dutch, and Danish coasts into the Skagerrack.

Height or Range of the Tides.—The extent of the rise and fall of the tides varies greatly in different places. By observations at islands in mid-ocean it is found that there the difference between high and low water is only 2 or 3 feet (Fig. 80), whereas in the comparatively shallow water near coasts, and especially in gradually narrowing bays and gulfs, the height is often very great, owing to retardation by friction

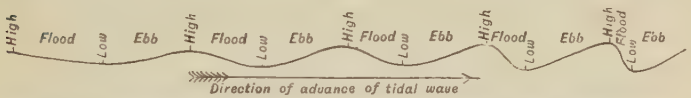


FIG. 80.—To illustrate the small range of the tidal wave in deep water, and the equal duration of flood and ebb tide there; but that in shallow water the range increases, the length from crest to crest decreases, and that the front of the wave becomes steeper than the rear, that is, the duration of flood tide shorter than that of ebb tide.

at the bottom and to lateral compression. For example, at New York the range at spring tide is $5\frac{1}{2}$ feet; at Portsmouth and Plymouth, 12 feet; at London, about 19 feet; at the mouth of the Bristol Channel it is only 10 feet, while at Bristol it amounts to 50 feet; and at the entrance to the Bay of Fundy, Nova Scotia, it amounts to 8 or 9 feet, but this gradually increases onwards to 50 or 60 feet at the head of the bay, and has sometimes, with a favourable on-shore wind, been as much as 100 feet.

It must be understood that the tidal disturbance extends, although with diminishing amplitude, right to the bottom of the deepest sea.

Length and Velocity of the Tidal Wave.—If the waters completely covered the globe, a double tidal wave would travel round it every day, and its length (that is, the distance between crest and crest) would be half the circumference of the earth, and its velocity at the equator about 1050 miles an hour (25,000 miles in 24 hours). Since at

every place on the sea-coast there are two tides in 24 h. 51 m., the rule is that the speed is such that the wave travels its own length in 12 h. $25\frac{1}{2}$ m. The tidal wave is longest, of greatest velocity, and least height, in deep water (see Fig. 80). For example, in water 3 miles deep the tidal wave is nearly 6000 miles long and travels nearly 500 miles an hour, and in water 40 feet deep the length is only 300 miles and the velocity 25 miles an hour. In fact, so constant is this relation that from the observed velocity we can compute the approximate depth of the sea. For instance, in the North Sea the tidal wave travels on an average 45 miles an hour, which corresponds to an average depth of 140 feet.

Only the Wave-form travels.—After what was said about wave-motion on p. 44, no reader will make the mistake of supposing that the waters of the ocean travel bodily from one region to another. Only the form of the wave travels westwards, the particles merely rise and fall, their advance during flood tide and recession during ebb tide being very slight, except where the tidal wave strikes upon a coast.

Tidal Currents.—In shallow water friction retards the lower portion of the tidal wave more than the upper, which therefore moves forward as a true current. In this way the simple up-and-down motion of the deep ocean is converted in shallow water into currents, which advance with the flood tide and recede with the ebb, as in the seas separating our islands from each other and from the Continent. In the Pentland Firth the current when at its strongest runs 10 miles an hour, or two or three times as fast as most of our rivers. When tidal water rushes in this way as a powerful and swift alternating current through narrow channels it is termed a *race*, as the Pentland Race, Portland Race, etc. When the channel is irregular and winding it gives rise to dangerous *eddies* or *whirlpools*, such as the eddies in the Kyles of Skye, or the famous whirlpool of Corryvreckan between the islands of Jura and Scarba, or the still larger Maelström among the Lofoten Islands.

Bores.—If the mouth of a tidal river is about the same width as the rest of its channel, then the range of the tides gradually becomes less and less up-stream, owing to friction. But if, on the other hand, a river has an estuary opening like a funnel towards the advancing wave, its tidal phenomena are peculiar. The opposition of the seaward current of the river,

the retardation due to the shallowness, and the lateral compression due to the gradual narrowing of the channel, cause the water of the tidal wave to be heaped up, and its front slope to become almost perpendicular (Fig. 80), so that the flood tide takes the form of a swiftly advancing and destructive wall of foaming water called a *bore* or *eagre*. The rise from low to high water is sudden, and ebb tide occupies the remainder of the 12 h. $25\frac{1}{2}$ m.

Bores occur in several British rivers, such as the Severn, Trent, and Solway, and in the Seine, Hooghly, Tsien-tang, Amazon, and the Petitcodiac River flowing into the head of the Bay of Fundy, etc. In the Hooghly mouth of the Ganges the bore is sometimes 7 feet high, and travels at the rate of 20 to 25 miles an hour. In the Tsien-tang in China the bore at spring tides reaches a height of 25 feet or 30 feet, and advances 80 miles up the river at the rate of 25 miles an hour.

Comparison of Tidal Waves and Wind-waves in Water.

Tidal Waves.	*Wind-waves.*
1. Caused by the differential attraction of the moon for the waters of the ocean and the solid earth. The sun acts similarly.	1. Caused by the friction of the wind on the surface of the water.
2. Only the form of the wave travels. The particles of water merely move up and down.	2. Same.
3. The movement extends to the bottom of the deepest ocean.	3. Only a thin layer of the surface water is disturbed.
4. The height varies, but in the mid-ocean it is only between 2 and 3 feet. The waves are so flat that they never form breakers upon an open coast.	4. The height varies from mere ripples up to between 50 and 60 feet in mid-ocean. The waves form breakers near a coast.
5. Their theoretical length is half the circumference of the globe. Their actual length varies from 6000 miles downwards, according to the depth and openness of the sea.	5. Their length varies from half a mile downwards, according to the depth of the water and force of the wind.
6. The velocity is so great that they travel their own length in 12 h. $25\frac{1}{2}$ m. In the Atlantic it is about 700 miles an hour, and in the North Sea about 45 miles an hour.	6. The greatest velocity is about 80 miles an hour, and for an average storm-wave about 37 miles an hour.
7. They are periodic and regular in their movements in any locality.	7. Their movements depend upon the wind.

Tidal Interference.—Eccentricities of the tides occur at

many places because of tidal interference. (*a*) Owing to the configuration of the land, the tidal wave may get broken up into two parts, and each part may pass a place beyond at different times, in which case the place will have four high tides in the course of the day. The four high tides daily at Colombo are referred to this cause. (*b*) Or the parts may subsequently combine so as to produce a very high tide at a place. The exceptionally high tides in the Bay of Fundy, for instance, are partly due to the fact that two tidal waves meet at its mouth. (*c*) Or the one part may closely follow the other at a place, and the effect will be to prolong the period of high water; *e.g.* at Havre high water lasts 3 hours. (*d*) Or, finally, they may follow each other at intervals of about 6 hours, in which case the trough of the one wave will coincide with the crest of the other, so that the two waves will neutralize each other and the region will be tideless. At Portland, for example, there is exceedingly little rise and fall of the water.

Southampton, not far from Portland, enjoys the convenience of four high tides a day. High tide lasts for about 3 hours, then it falls slightly and afterwards rises again for 1½ or 2 hours before it begins to fall to low water. This peculiarity seems to extend across the English Channel, and therefore can hardly be due to the Isle of Wight. It seems rather to be due to reflection of the tidal wave by the French coast, so that the main wave advancing up the Channel is followed pretty closely by the reflected wave.

Tides in Lakes and Land-locked Seas.—Theoretically there are tides produced in all water surfaces on the face of the earth, but the length from east to west of even the largest sheets of water cut off from the great oceanic tidal wave is too small in comparison with the length of the wave (half the circumference of the earth) for any considerable part of it to form. Consequently, the tidal rise and fall in enclosed seas are very slight, and are often completely masked by the variations of level caused by local winds.

In the great American lakes the tides are almost imperceptible. A tide of less than two inches has been detected in Lake Michigan, and one of less than an inch in Lake Erie.

In the Baltic the tide only rises a few inches. Even in open parts of the Mediterranean the tidal rise and fall is only 3 or 4 inches. For instance, at Algiers the fluctuation of level is 3½ inches at spring tides. At other places the range is about 18 inches. But at the head of some bays and long gulfs like the Adriatic, the range may be 3 or 4 feet. In the Straits of Messina the strong tidal current gives rise to the whirlpools "between Scylla and Charybdis."

Effects of the Tides.

1. ASTRONOMICAL.

(*a*) *Effect on the Earth's Rotation.*—When the tidal wave strikes the shores of continents, a considerable amount of its energy is dissipated in the form of heat. But this energy lost through the tides must be abstracted from some source or other, and it has been proved that it is derived from the energy of the earth's rotation. Whence it is evident that the ebb and flow of the oceans act as a friction-brake upon the earth, whose period of rotation is thereby lengthened. There are, however, counteracting influences; and it seems that the increase in the length of the day produced by tidal action is almost the same as the decrease due to the more rapid rotation of the earth caused by its cooling and contraction. If the day is really growing longer, the change cannot be as much as the $\frac{1}{1000}$ part of a second in 1000 years.

(*b*) *Effects on the Moon's Motion.*—But the whole of the energy of rotation lost by the earth is not dissipated by the tides. A part of it is spent upon the moon in a way which cannot be explained here, thereby causing an increase in the rate of revolution, and therefore the distance, of our satellite. Upon this inter-action between tides and the motion of revolving bodies Professor G. H. Darwin has based his theory of the "tidal evolution" of systems. According to it, the moon seems to have been originally part of the earth when in the semi-fluid condition, and to have been whirled off from it by the earth's rapid rotation which took place at that time in only a few hours. Since then the moon has gradually receded from the earth for the reason stated above. Also, while the moon was still near and in the plastic molten condition, the earth must have generated very large tides upon it, which would act as friction-brakes until the moon's period of rotation became the same as its time of revolution round the earth.

2. GEOLOGICAL.

(*a*) *They act as denuding agents* because of their currents and continual ebb and flow. At one time, when the moon was much nearer, the tides must have been higher and their denuding action far greater than at present.

(*b*) *They help to form bars and shoals in tidal rivers.* During ebb tide the mud and sand brought down by a river are carried out to sea, and during flood tide part of the sediment is brought back and deposited here and there, forming sandbanks and shoals.

QUESTIONS.

1. Name the different kinds of lakes, and tell what you know of the origin of each kind.

2. Explain the reason of the constant filling up of lakes. State the theories that have been proposed to account for the origin of lakes.

3. Tell what you know concerning the cause of sea-waves, their size and speed, and the depth of water affected by them.

4. Describe some simple observations which point to a connection between the moon and the tides.

5. Draw a diagram, and by reference to it show clearly (*a*) that there are two tides at the same time; (*b*) how it is that high water does not recur at the same hour daily.

6. How is it that there are, in general, *two* high waters and *two* low waters in a day?

7. Explain the more powerful differential action of the moon in causing the tides.

8. The sun's attraction at the earth's surface is much greater than that of the moon, yet the moon is the more important agent in producing tides. State the exact reason of this.

9. What is the difference between spring tides and neap tides? What determines the time of the occurrence of spring tides and neap tides?

10. About what hour of the day does the high water of spring tides occur at a place, and about what hour of neap tides?

11. Explain the terms "spring tide," "neap tide," "priming and lagging," "establishment of the port."

12. How could you find the time of high water at London Bridge if you were given a table showing when the moon was on the meridian, and you knew that the "establishment" at London Bridge was 1 h. 58 m.?

13. Give a general description of the course of the tidal wave round the globe.

14. Atlantic tides come from the south, Mediterranean tides from the east. Explain.

15. Explain by the aid of a sketch-map the course of the tidal wave around the British Islands.

16. Explain (*a*) why it is "full" tide at Greenock nearly 3 hours earlier than at Leith; (*b*) why the time of high water at any place is subject to daily change.

17. Define "range of tide," and mention a place in the British Isles where the range is small, and one where it is large.

18. Mention some peculiarities of tidal range along the south coast of England, and explain their causes.

19. What is a "bore"? How are bores produced? Name three rivers which exhibit this phenomenon.

20. Compare tidal waves with wind-waves in water.

CHAPTER XII.

OCEAN DEPTHS AND DEPOSITS.

The Old Method of Sounding consisted in attaching a mass of lead to a strong hempen rope, which was divided into fathoms by coloured pieces of cloth tied round it. A man in the bow of the ship threw out the lead, and the alteration in the rate at which the line ran out was supposed to tell when the bottom was reached, and then the depth was known by the coloured pieces of cloth.

To tell the nature of the ocean-bed the lead was "armed," that is, in the bottom of it there was a shallow cup-shaped depression filled with tallow, to which some of the material at the bottom adhered and was brought up.

By this method the depths obtained were often greatly exaggerated. Some parts, for example, were said to be 7 miles deep, and others unfathomable, for the line went on running out indefinitely.

The chief causes of error—

1. If the depth was great, the line always broke in the attempt to bring up the weight, owing to the great pressure of water upon it, and to the friction caused by the movement of the great length of rough rope in the water. Hence there was no sure evidence that the bottom had actually been reached.

2. The rope was of less specific gravity than the water, so that if sufficient length of it were out it would float the weight and prevent it from reaching the bottom.

3. Even although the weight did reach the bottom, there would be difficulty in telling when it did so, for strong currents would still continue to drag out the rope. Also under-currents would float the rope out of the perpendicular, and perhaps form tangle after tangle, as shown in Fig. 81, so that the actual depth could not be told with any certainty.

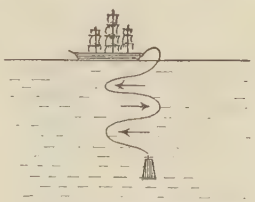


FIG. 81.—To illustrate how under-currents may affect deep-sea soundings when a hempen line is used.

The above method, although useless for the deep sea, might, because of its expeditiousness, be useful for surveying roadsteads and the sea-bottom along coasts, or for rapidly telling a navigator the depth of the sea and the nature of the bottom near a coast but out of sight of land.

The Modern Methods of Deep-sea Sounding.

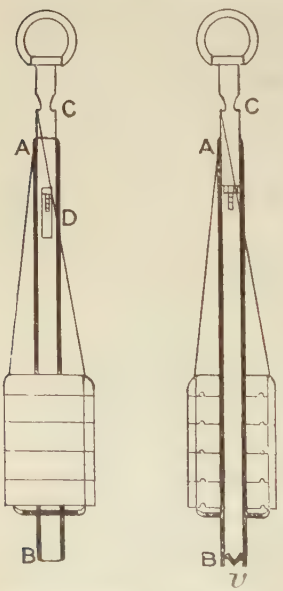
The chief improvements in the modern methods are—

1. Using strong pianoforte wire instead of rope. The great merit of wire is the smoothness of its surface and the smallness of its area compared with rope of the same strength. This allows the sinker to descend more quickly, and also makes it easier to get the line on board again. Also the wire, being of greater specific gravity than sea-water, does not float, nor is it so readily affected by under-currents.

2. The weight is detached as soon as it strikes the bottom, leaving only a tube containing a specimen of the ocean-floor to be brought up.

3. Therefore a sufficiently heavy weight can be used in order to reach the bottom quickly, with the line as nearly as possible in a vertical position.

The Baillie sounding-machine, so called after its inventor, Lieutenant Baillie, R.N., was used in the *Challenger* Expedition (1872–76), and is represented in Fig. 82. The sounding-line consists of strong wire. At the end of it is an iron tube, AB, about $5\frac{1}{2}$ feet long by $2\frac{1}{2}$ inches in diameter, and having at the lower end a pair of valves, *v*, opening inwards. A heavy piston of iron, C, can slide upwards and downwards in the upper part of the tube, the distance it can move being the length of the slit D in the tube, through which a screw nut attached to the piston projects. The sounding-rod projects about 18 inches through the centres of several cylindrical cast-iron sinkers, each 56 lbs. in weight (1 cwt. being allowed for each 1000 fathoms expected). The weights are supported at C by a wire sling hooked upon a projecting shoulder of the piston. So long as the apparatus is descending, the tension of the



Baillie's sounding-machine. Section of same.

FIG. 82.

sounding-line keeps the nut at the top of the slit; but the moment the ocean-bottom is reached, the tube is pushed up the length of the slit D. The top, A, of the tube in this way comes up to the projecting shoulder C of the piston, and throws off the sling and sets free the sinkers. The tube is forced some distance into the mud, so that a specimen of the bottom is obtained and prevented by the valves from escaping. The rod is then pulled up, and the weights left behind.

It is known when the bottom is reached by the sudden change in the rate at which the line has been running out. How much line has then run out is known, and this is the depth.

Attached to the line are also—

(1) A water-bottle, a short distance above the rod.

(2) A pressure-gauge to register the pressure due to the superincumbent water.

(3) Deep-sea thermometers at fixed intervals, such as every 100 fathoms along the line.

Thus in a sounding we obtain—

(1) The depth.

(2) A sample of the materials at the bottom.

(3) A sample of the water at the bottom.

(4) The pressure at the bottom.

(5) The temperature of the sea at every 100 fathoms from the surface to the bottom.

Lord Kelvin has invented a deep-sea sounding-machine rendering it unnecessary to leave the weights at the bottom so long as the depth does not exceed 3000 or 3500 fathoms. He uses a steel wire line and a 30 or 35 pound sinker, with no detaching apparatus. He claims for his machine that it is surer than the above instrument, is simple, inexpensive, does not require steam-power to haul it in, and does not leave three or four hundred pounds of cast-iron at the bottom every time a sounding is made. A description of it is given in his *Popular Addresses*, vol. iii. p. 347, etc.

Lord Kelvin's Navigational Sounding-machine is designed for the purpose of taking flying soundings (that is, soundings from a vessel running at full speed) in water of any depth not exceeding 150 fathoms. The line used is the best quality of steel pianoforte wire, galvanized to keep it free from rust, and only 0·03 inch in circumference, and bearing a strain of from 230 to 240 lbs. without breaking. Such a wire combines the advantage of great strength with a small resistance to motion through the water, so that two men can easily take a sounding from a vessel sailing 16 knots. The line is wound round a V-shaped groove in the rim of a light wheel, and the moment that the weight reaches the bottom is indicated by a

sudden decrease in the speed of rotation of the wheel. The number of revolutions of the wheel is recorded, and this gives the depth. The line is then hauled in by turning the wheel by means of two handles, and two men can easily perform this operation, as only three or four hundred fathoms of wire have run out (allowing for the non-verticality of the line).

A metal cylinder over 3 feet long is used as the sinker, and at the bottom it is armed with tallow in the usual way, to bring up a specimen of the sea-floor. The depth that the sinker has reached vertically from the surface is found in a very ingenious manner. The sinker is a hollow tube, and inside it is placed a *depth-recorder*, which tells the amount of compression of the imprisoned air, and is founded on the principle that if the pressure is known the depth can be calculated because the pressure increases at a certain rate with the depth. The recorder consists of a straight glass tube open at the lower end, and protected by a copper sheathing. The inside of the glass tube is coated with chromate of silver, which is orange-coloured. As the instrument descends, the pressure of the water increases, and some of the water is therefore forced up into the tube and compresses the air in it. The sodium chloride in the sea-water acts on the chromate of silver, changing it into chloride of silver, which is white in colour, and, being insoluble in sea-water, remains on the glass as far up as the water has been forced into the tube. We can thus tell how much the air has been compressed, and therefore the pressure to which it has been subjected, and hence the depth. But to save the trouble of making these calculations, a box-wood scale is supplied with the instrument, by which we can at once tell the depth from the length of the discoloration.

The advantages of a shallow-water sounding-machine by which soundings can be made with ease and certainty, whatever the speed of the vessel, cannot be over-estimated. Sometimes shipmasters, near a coast, but out of sight of land, have let hours go by without obtaining soundings, either because of the delay involved in stopping the vessel or of the danger of doing so in heavy weather. In shallow water in foggy weather it is essential at short intervals to know the depth of the sea and the nature of the bottom, and then, by comparing these particulars with the charts, to know the whereabouts of the vessel, and whether the proper course is being kept. The instruction printed on the box containing the machine is, "WHEN NEAR SHORE OR WITHIN 100 FATHOMS IN THICK WEATHER, KEEP THE MACHINE GOING INCESSANTLY, TWO MEN WORKING IT AND ONE TO RELIEVE." A sailors' maxim is "lead, log, and look-out," and, as Lord Kelvin has said, only by the neglect of this need a vessel be lost by running on the rocks in thick fog.

Results of Soundings.—The reader should revise what was said on this subject in the elementary book, pp. 183–187. (See also Fig. 83 on the page following this.)

Pressure in the Ocean.

1. *Its measurement* is made by means of a pressure-gauge attached to the sounding-line. Lord Kelvin's depth-recorder is really a pressure-gauge. A common form of gauge based on the same principle consists of a glass tube open at the bottom, and coated on the inside with prussiate of potash. The glass tube is placed inside a brass one open at the top and closed at the bottom. The glass tube contains air, and the brass one a solution of sulphate of iron. As the instrument is lowered, the increased pressure forces some of the iron sulphate into the glass tube, where it acts chemically on the yellow or red prussiate of potash, turning it into a deep blue colour. When the gauge is drawn up, the pressure is known by comparing the length of the discoloration with a prepared graduated scale.

2. *The increase of pressure with depth* is at about the rate of 1 ton per square inch for every 1000 fathoms vertically below the surface, so that the average pressure at the bottom of the ocean is about $2\frac{1}{2}$ tons per square inch, and in the deepest parts of the ocean it amounts to 4 or 5 tons per square inch.

3. *Effects of Pressure in the Ocean.*

(*a*) *On the Density of the Water.*—Water, like other liquids, is very slightly compressible, hence the rate of increase of density downwards in the ocean is very slow. For example, the specific gravity or density of sea-water at the surface is 1·026, at 100 fathoms 1·028, at 500 fathoms 1·031, and at 2000 fathoms 1·053.

(*b*) *On the Sea-level.*—The effects of this increase of density with depth are very important, for Professor Tait, from his experiments in connection with the *Challenger* Report, has proved that if the oceans were absolutely incompressible, the level of their surface would be 116 feet higher than at present, and about two million square miles of the habitable surface of the globe would be submerged.

(*c*) *On the Deep-sea Fauna.*—There are no plants at the bottom of the ocean, but animals in considerable abundance, and these are specially modified to bear the enormous pressure. For this reason they are invariably dead when brought to the surface, their eyes starting out of their heads, their swimming

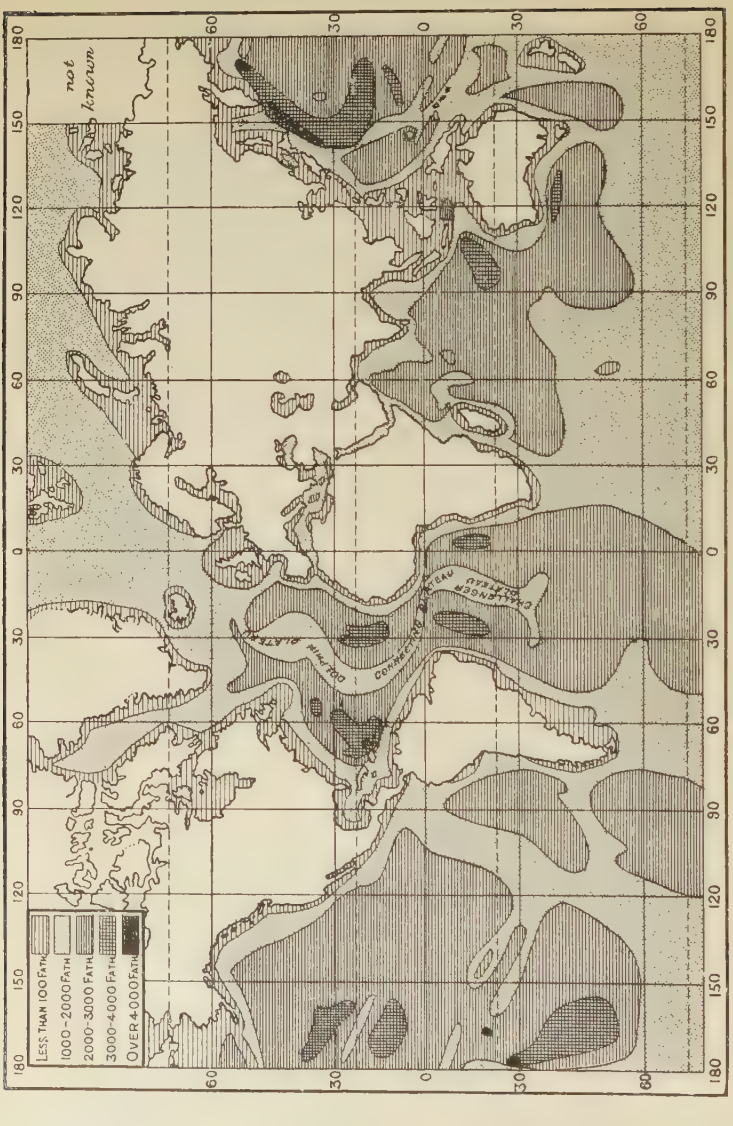


FIG. 83.—Approximate depths of the oceans (chiefly from the *Challenger* Report).

bladders forced out at their mouths, almost all the scales stripped off their bodies, and every muscle loosened.

(*d*) *On the Chemical Action.*—There is evidence of extensive chemical action at the sea-floor, and some believe that this increased activity is due to the great pressure. It may, however, be due to the action of the large amount of organic matter decomposing there.

Deep-sea thermometers are sensitive thermometers of the maximum and minimum type (p. 32). They are made of strong glass, but even this is an insufficient protection against the enormous pressure in the deeper parts of the ocean, which would either crush their bulbs or at least so compress them as to cause the readings to be too high. Hence the bulb is surrounded by a second one of very strong glass, the space between the two bulbs being *partially* filled with mercury or alcohol, which readily conducts the heat of the water to the inner bulb. If the space between the bulbs were totally filled with the liquid, then on the outer bulb being compressed it would compress the liquid, which in turn would hand on the compression to the bulb of the thermometer, and so cause erroneous readings. But part of the intermediate space is occupied by the vapour of the liquid, which, being easily compressible, shields the thermometer from compression.

To protect the instrument from being broken by knocking against the line, it is placed in a copper sheath perforated at the top and bottom to freely admit the water whose temperature has to be determined.

The surface temperature of the ocean varies with (1) latitude, (2) day and night, (3) the seasons, and (4) the nature of the winds and currents.

1. *Latitude.*—In equatorial regions the surface of the sea has sometimes a temperature of 85° or 86° F., and in the greater part of the tropical zone the surface temperature is higher than 80° for the whole year. This belt of warm water is widest in the Indian Ocean, and narrowest in the Atlantic, and is wider in the western than the eastern parts of the oceans. Enclosed tropical seas comparatively undisturbed by winds and currents have the highest temperature of all. For example, 91° F. has been recorded on the coast of Siam, and in the Red Sea readings from 90° to 100° F. have been obtained near its south end.

In polar regions the average surface temperature is about 30° F. This difference between the frigid and torrid zones is

due to the fact that the sun is almost vertical in the latter all through the year, and therefore less of his heat is absorbed by the atmosphere before reaching the surface of the sea.

Between the equator and the poles the temperature of the surface water decreases pretty regularly with latitude. The northern part of each ocean is warmer than the southern, because the former is more influenced by warm equatorial currents, while the latter is more open to cold polar currents and floating icebergs. To cite but one example, Dublin and Port Famine, in the Straits of Magellan, are at practically the same distance from the equator, the one in the northern hemisphere and the other in the southern, yet their mean summer temperatures are respectively 66° and 50° F., mean winter temperatures 39° and 33° F., and their mean annual temperatures 49° and 43° F.

2. *Diurnal Variation.*—Because of the great specific heat and low radiating power of water, the temperature of the surface of the sea varies little by day and night—probably not more than 1° F.

3. *Seasonal Variation.*—For exactly the same reasons as stated in the last case, the surface of the sea in the northern hemisphere is warmest in August and coldest in February—a month later than the corresponding turning-points in the temperature of the air over the land. The annual variation in the temperature of the sea is very small in the torrid and frigid zones, while even in the temperate zones it is little more than 10 F. Around Great Britain, for example, the surface temperature of the sea varies from 60° F. in August to 49° F. in February.

4. *The Influence of Winds and Currents* must, of course, be taken conjointly, since currents are determined by prevailing winds. For instance, the north-east and south-east Trade Winds produce the western equatorial currents which cause the western sides of tropical oceans to be warmer than the eastern. Owing to the Gulf Stream, the surface temperatures in the North Atlantic are higher than in corresponding latitudes in the North Pacific. Indeed, if we consider the great specific heat of water, we may form some idea of how much the warm currents from the equator to the poles, and the cold return currents from the poles to the equator, raise the surface temperatures towards the poles and lower them at the equator.

The temperature of the ocean at different depths below the surface is obtained by deep-sea thermometers

attached to the sounding-line at certain intervals, such as every 100 fathoms.

Only a small part of the sun's heat is arrested at the surface of the ocean. It penetrates to a depth of 60 or 80 fathoms. But even below this, probably to an average depth of about 500 fathoms, the sun indirectly affects the temperatures by means of surface currents. At this depth all fluctuation ceases, and the water is at 40° F. in all latitudes and at all seasons; consequently, the fall of temperature from the surface down to the stratum of constant temperature is rapid in the tropics, and much less abrupt in the regions to the north and south. The late Sir Wyville Thompson, director of the *Challenger* Expedition, very well described the temperature conditions of the open ocean thus: "At a depth varying in different parts of the world, but averaging perhaps 500 fathoms, we arrive at a layer of water at a temperature of 40° F. . . . Above this band the temperature varies greatly over different areas, while beneath it the temperature almost universally falls very slowly, and with increasing slowness, to a minimum at the bottom" (see Fig. 84). On the ocean floor, especially where it is very deep, the temperature may be 35° or 32° F., and temperatures even below the freezing-point of fresh water have in some places been registered. These low temperatures are due to icy-cold indraughts creeping along the bottom from polar regions towards the equator, for (*a*) the temperature of the water at the bottom is lower than that of the earth's crust underneath, and therefore cannot be derived from it; and (*b*) we do not find ice-cold water at the bottom of seas that neither directly communicate with polar seas nor with the depths of oceans that do.

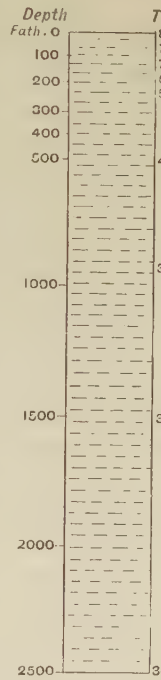


Fig. 84.—Diagram to show the average decrease of temperature with depth in a column of water at the equator. Observe the rapid fall of temperature near the surface.

By far the larger part of the cold abysmal water, even in the northern hemisphere, comes from the Antarctic Ocean, for the

configuration of the continents and of the ocean-floor freely allow deep-sea currents to flow to the north from Antarctic regions, whereas cold Arctic water can only get south into the Pacific through Behring Strait, and into the Atlantic the underflow is checked by the long submarine ridge on which Iceland stands, and which rises everywhere to within 500 fathoms of sea-level, the only open channels left from Iceland to Labrador being the comparatively narrow ones on either side of Greenland.

Temperatures in Land-locked Seas.—In enclosed seas the temperature varies for a certain distance downwards, and then remains uniform down to the bottom. If a sea is cut off by a barrier from the great oceanic basins, the temperature of the water remains the same from the level of the barrier down to the bottom. This is well illustrated in the Mediterranean and Caribbean seas, and in several of the partially enclosed seas on the east of Asia.

The Strait of Gibraltar is very shallow (200 fathoms), and the deepest part of the current flowing through it from the ocean is about 125 fathoms; hence in the Mediterranean the temperature falls from above 70° F. at the surface to 55° F. at a depth of 125 fathoms, and the water remains steadily at this temperature right down to the bottom, while in the Atlantic at the latter depth the temperature is as low as 35° F.

The Caribbean Sea and Gulf of Mexico have a temperature of 39½° F. from 1000 fathoms to the bottom, and it has been found that this is the greatest depth of the channels from the Atlantic. The Red Sea has a depth of 1200 fathoms at its centre, but at the Strait of Babel-Mandeb it is separated from the Indian Ocean by a submarine ridge only 200 fathoms from the surface. The temperature of the surface of the Red Sea is over 85° F. in summer, and 70° in winter. At a depth of 200 fathoms the temperature is 70° F. (the same as in the Indian Ocean at the same depth), and remains at this right down to the bottom all the year through, whereas in the Indian Ocean the temperature at 1200 fathoms is 37° F.

Animal and Vegetable Life in the Ocean.—(*a*) To procure specimens at the surface a net is used, and for microscopic organisms "tangles" (that is, lengths of unspun rope) are employed. As the tangles are dragged along the surface, the creatures adhere to them and get caught. (*b*) For intermediate depths a network bag very close in the mesh is employed, and to catch small organisms that could easily pass through the meshes, one or two "tangles" are attached to the bottom of the bag. The jaws of the bag are of iron, and there is an arrangement for opening and closing them at the required depth, so that the organisms only enter there, and not while the bag is being lowered or raised. (*c*) To bring up specimens

from the bottom a trawl-net is used, which is slowly dragged along in a horizontal position. Two pieces of metal projecting from the pole of the trawl prevent the open lip of the bag from quite touching the bottom and so getting torn by inequalities there.

Animal and vegetable life is most abundant in the first 100 fathoms. *No plants are found at a greater depth than half a mile*, but animals are found at all depths, although in diminishing abundance as the depth increases, and then near the bottom they somewhat increase again. There is, however, a paucity of animal life in the depths of the Mediterranean and other inland seas. This is due to the deep waters being to a certain extent stagnant, owing to the absence of the cold bottom currents so marked in the open oceans.

All oceanic life falls into two great divisions :—

1. *Plankton* (Gr. *planaomai*, "I wander, roam about"). This division includes all plants and animals which are free to wander about at the surface or intermediate depths of the ocean, either by swimming or by passively floating with winds and currents.

This division comprises an immense number of plants and animals, from microscopic algæ to huge cetaceans (whales). Amongst plants it includes such algæ as diatoms, coccoliths, and rhabdoliths, etc. ; and in the animal kingdom it includes such invertebrates as the foraminifers, molluscs, crustaceans, radiolarians, etc., and such vertebrates as the whole family of fishes, seals, walruses, cetaceans, etc. Some of these have already been pretty fully described in the elementary book, pp. 220–222. The following have the power of abstracting either carbonate of lime or silica from the sea-water, and when they die their skeletons collect and form important geological deposits :—

Animals that abstract carbonate of lime from water	Foraminifera, *e.g.*	Globigerina.
		Orbulina.
		Pulvinulina, etc.
	Mollusca, *e.g.*	Pteropoda.
		Heteropoda, etc.
	Crustacea.	
	Echinoderms, *e.g.* encrinites.	
	Coral polyps.	
Plants that abstract carbonate of lime from water	Coccoliths and coccospheres.	
	Rhabdoliths and rhabdospheres.	
	And other calcareous algæ.	
Animals that abstract silica from water	Radiolaria.	
	Siliceous sponges, etc.	
Plants that abstract silica from water	Diatoms.	
	And other siliceous algæ.	

2. *Benthos* (Gr. *benthos*, "the bottom of the ocean"). This division includes all organisms attached to or creeping along

the bottom of the ocean. Until it became necessary to make soundings in connection with the laying of cables, it was considered that oceanic life was limited to a depth of 300 fathoms. We now know that, while life is incomparably more abundant in the shallow water near shore, yet even in extreme depths animals live in considerable abundance, there being, in addition to fish, large numbers of echinoderms such as star-fish and sea-urchins ; various shrimp-like crustaceans ; and comparatively few molluscs such as pteropods and heteropods, etc.

Peculiarities of the Deep-sea Animals :—

(1) *Their wide distribution.* After reaching a depth of about half a mile, the same genera are found in all the great oceans. In these deep waters, the same or allied species are dredged off the coast of Britain and at the antipodes.

(2) *Their size.* A few of the deep-sea animals are larger than the corresponding shallow-water forms, but the majority are dwarfed, and delicate in appearance, their tissues flabby and feebly developed, and their shells poorly supplied with carbonate of lime and silica.

(3) *They are adapted to the enormous pressure* and severe cold that characterize the great depths of the sea. We referred to this on p. 175.

(4) *Their eyes.* It is believed that sunlight does not penetrate the waters beyond a depth of 400 or 500 fathoms. Hence some of the fishes at very low levels are blind, their eyes having deteriorated in structure and become rudimentary, and instead of them they have developed long antennæ or feelers for finding their way about. The eyes of other deep-sea animals are exceedingly large, as if to grasp as much as possible of what little light there may be. This light is artificial in character, being produced by some of the fishes whose bodies (or parts of them) are phosphorescent. Some exceptional creatures have special searchlights and reflectors, and complicated electrical apparatus.

(5) *Their colour* is always protective—for concealment either from their enemies or from their prey. Many agree in colour with the mud or ooze at the bottom. It is observed that with increasing depth well-defined markings, such as bands and spots, disappear, and the colour of a fish becomes more uniform, and usually a brown or black.

Marine deposits may be divided into two great classes, viz. terrigenous deposits and pelagic deposits.

Terrigenous deposits are, as their name indicates, made up principally of the *débris* from the solid earth, and their fragments bear traces of the mechanical action of rivers, winds, waves, and currents. These materials surround the coasts of continents and islands (see Fig. 91, p. 190), and extend sometimes 200 or even 300 miles seaward, and it is estimated that they cover one-fifth of the bed of the ocean.

The terrigenous deposits differ in their physical characters according to the depth at which the sedimentation took place,

and are accordingly divided into littoral, shallow-water, and deep-sea varieties, the last mentioned being sometimes found in depths of 3000 or even 4000 fathoms.

Pelagic or abysmal deposits occur in the deepest parts of the ocean, at a considerable distance from the land. In them continental *débris* is nearly or quite absent, and they comprise five types—four being of organic origin and called oozes, the fifth and most extensive being of inorganic origin and called red clay.

The following is the classification adopted by Sir John Murray and Prof. Renard in their report on the deposits collected during the *Challenger* Expedition :—

MARINE DEPOSITS.

1. *Littoral deposits* (between high and low water marks)	Sands, gravels, muds, etc.	I. TERRIGENOUS DEPOSITS, formed in deep and shallow water close to land masses.
2. *Shallow-water deposits* (between low water mark and 100 fathoms)	Sands, gravels, muds, etc.	
3. *Deep-sea deposits* (beyond 100 fathoms)	Blue mud	
	Red mud	
	Green mud	
	Volcanic mud	
	Coral mud	
	Globigerina ooze	II. PELAGIC DEPOSITS, formed in deep water far away from land.
	Pteropod ooze	
	Radiolarian ooze	
	Diatom ooze	
	Red clay	

Littoral and shallow-water deposits consist of beds of sand (occasionally mixed with fine gravel), and layers of mud in the deeper and more remote parts. The bed of the shallow North Sea, for instance, consists of long banks of sand, with here and there hollows containing mud.

Deep-sea Terrigenous Deposits.—Beyond a depth of 100 fathoms the deposits gradually change in character, becoming finer, and the proportion of land detritus decreasing and that of organic remains increasing as the terrigenous deposits insensibly merge into the pelagic deposits. The materials are termed muds because they are soft and sticky when wet, and form a loose powder when dry.

1. *Blue Mud.*—Blue mud is the most widely distributed of the land-derived deposits now forming around continents and in all enclosed or partially enclosed seas. It is finely granular

in texture, and consists of argillaceous matter and mineral particles, chiefly of quartz, and also of felspar, mica, augite, hornblende, etc.—indeed, all the minerals derived from the disintegration of the neighbouring lands. It generally also contains a smaller or larger quantity of the shells of calcareous and siliceous organisms.

The colour of the mud is dark blue or slaty, but usually there is a thin upper layer of red or brown. The characteristic colour is due to chemical changes produced by decomposing organic matter. The decaying animal and vegetable substances in the deposit give off sulphuretted hydrogen, and this gas changes the ferric oxide in the mud into ferrous oxide and blue sulphide of iron, and it is this sulphide that gives the blue colour to the mud, and the thin upper film of red is due to the whole of the ferric oxide present not having been reduced.

2. *Red Mud.*—When there is more ferric oxide in the mud than the organic matter present can totally reduce, then the mud retains its red colour; as, for example, along the coast of Brazil, owing to the large amount of ferric oxide brought down by the Amazon, Orinoco, and other rivers.

3. *Green mud* has practically the same composition as blue mud, and owes its green colour to the presence of large quantities of grains of glauconite. This is a dirty-greenish mineral, composed of the hydrous silicate of iron, potash, and alumina. It occurs off cliff-bound coasts, where no large rivers pour their detrital matters into the sea, as along the west coast of the American continent or the south of Africa. In such localities deposits accumulate very slowly, and the finely divided mineral particles derived from the land are subjected for a long time to the chemical action of the sea-water and probably also of the organic matter present, and thus, in a manner as yet little understood, glauconite is formed. This greenish mineral fills up foraminiferal and other calcareous remains, forming in this way exact casts of the interior of the shells (see Fig. 85), and these casts may remain even after the shells themselves have been broken up or dissolved away.

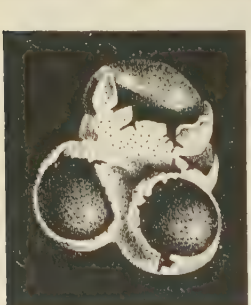


Fig. 85.—Glauconite grains in the shell of a globigerina. (From the *Challenger* Report.)

Green sand differs from the mud only in having larger grains

and less argillaceous matter, and in being formed in shallower water nearer the coast.

4. *Volcanic mud and sand* are deposited in the neighbourhood of volcanic islands, and consist mainly of particles of volcanic rocks and minerals. The coarse deposits near the coasts are called sands, the muds being finer in texture and formed in deeper water farther to sea.

5. *Coral mud and sand* occur in a similar manner around coral reefs and islands. The deposits consist mainly of fragments of corals, foraminifera, and other calcareous organisms.

The Oozes.—The remains of myriads of minute creatures are in all latitudes continually falling to the bottom of the ocean and accumulating there. Near the continents they are covered up by the terrigenous deposits, which are more plentiful. But in the abysmal regions farther from the land the continental muds die out and gradually give place to accumulations of organic remains more coherent and plastic than the muds, and going by the general name of ooze. It is called globigerina, pteropod, or radiolarian ooze if the shells of these animals predominate, and diatom ooze if the frustules or cases of this plant are in the majority.

Globigerina ooze contains over 40 per cent. (sometimes as much as 95 per cent.) of carbonate of lime, and consists

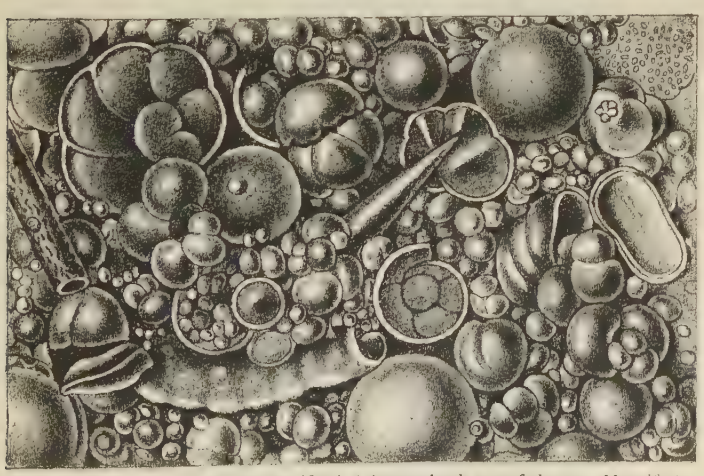


FIG. 86.—Globigerina ooze from the North Atlantic, depth 1900 fathoms. Magnified 25 diameters. (From the *Challenger* Report.)

chiefly of the shells of dead foraminifera, especially the species *Globigerina*, *Orbulina*, *Pulvinulina*, etc. In addition to these there occur various other calcareous organisms, such as pteropods and heteropods, coccoliths and rhabdoliths. The remains of siliceous organisms, such as radiolarians and diatoms, occur in variable quantities, sometimes forming 20 per cent. of the deposit, and at other times being present only in very small quantity. Chemical analysis shows also the presence of argillaceous matter, and the oxides of iron and manganese.

Globigerina ooze is fine-grained, and forms a soft and sticky mud when wet. Its colour may be white, yellow, brown, or red, depending chiefly on the relative abundance of the two above-mentioned oxides.

The map, Fig. 91, p. 190, shows that this deposit has a wide distribution, being found in tropical and temperate latitudes of the Atlantic, Pacific, and Indian oceans (especially the first-mentioned), at depths ranging from 300 up to 2500 fathoms, and covering altogether nearly 50 million square miles of the ocean floor.

Pteropod ooze is of the same general character as globi-

FIG. 87.—Pteropod ooze from the North Atlantic, depth 450 fathoms. The illustration shows shells of pteropods and other molluscs, and also foraminifers. Magnified 5 diameters. (From the *Challenger* Report.)

gerina ooze, differing from it only in the greater abundance of the shells of such molluscs as pteropods and heteropods,

and in occurring usually in lesser depths—up to 1500 or 1700 fathoms. It covers only about 400,000 square miles in the Atlantic.

Radiolarian ooze is the name given to a deposit when the remains of radiolaria form more than 25 per cent. of it. It contains also the spicules of siliceous sponges, and calcareous

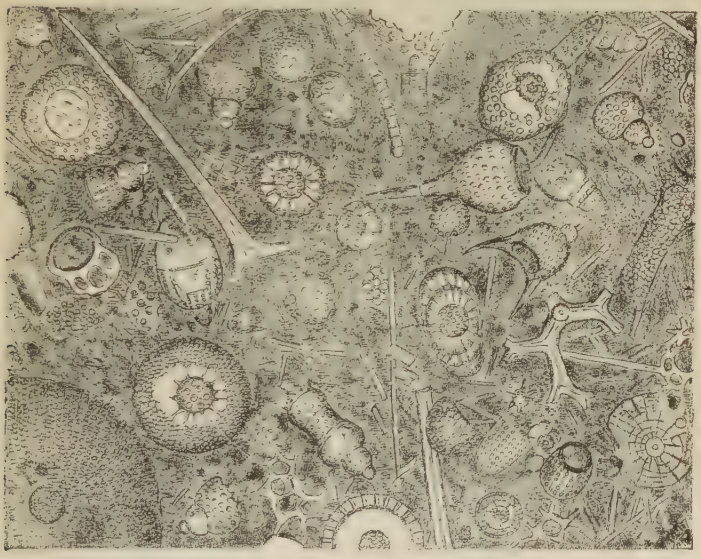


FIG. 83.—Radiolarian ooze from the Central Pacific, depth 4475 fathoms. Shows shells of radiolaria and spicules of siliceous sponges. Magnified 100 diameters. (From the *Challenger* Report.)

remains, and mineral particles are nearly always present in it in smaller or larger quantities. Its colour is reddish or deep brown, owing to the presence of the oxides of iron and manganese. It is found in the deepest parts of the ocean. It occurs in the Central Pacific and the east of the Indian Ocean, but has not been found in the Atlantic Ocean.

Diatom ooze is a deposit about 50 per cent. of which consists of the cases of diatoms, mixed with which are remains of radiolaria, sponge spicules, and about 25 per cent. of carbonate of lime in the form of shells of globigerinæ, etc. It is of pale straw colour, and when dry it forms a dirty white flour. It is the distinctive deposit of the Antarctic and

southern oceans, where it occurs at all depths. It has also been found in the north-west Pacific.

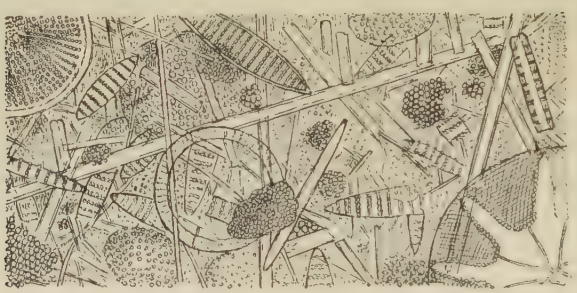


FIG. 89.—Diatom ooze from the Indian Ocean, depth 1950 fathoms. Magnified 300 diameters. (From the *Challenger* Report.)

As diatoms were not described in the elementary work, we may briefly do so here. They are extremely minute forms of vegetable life, requiring microscopes of the highest power to render them visible. Each consists of a single cell of protoplasm, which can, however, form siliceous skeletons of thousands of different varieties by abstracting silica from the sea, lakes, rivers, etc. All the skeletons consist of two parts, practically three, viz. two parts either round discs or boat-shaped (see Fig. 89), and a kind of girdle binding these two parts together. The shells are sculptured and perforated with holes arranged in most beautiful patterns. Inside the shell is the protoplasm, while the outside during life is covered with a slimy greenish substance.

Fresh-water types, smaller than the salt-water varieties, occur in great numbers in any lake, pond, or ditch, and their remains form deposits 20 to 35 feet thick in some lakes.

Red clay is a stiff clay found far from continents, in parts of the ocean deeper than 2500 fathoms. It is greasy to the touch, and plastic when wet, but very hard when dry. It owes its colour to the oxides of iron and manganese. When the constituent particles have a surface coating of ferric oxide, the colour of the clay is brick-red, and when grains of manganese dioxide are numerous, the deposit assumes a chocolate-brown colour.

Red clay is the most widely distributed marine deposit, for it is spread over an area of 51½ million square miles, or about the same as the total area of the land-surfaces of the globe. The map at p. 190 shows that it covers the greater part of the Pacific, as well as extensive tracts of the Atlantic and Indian oceans.

Red clay is composed almost exclusively of the minerals which occur in volcanic rocks, together with particles of volcanic dust and fragments of lapilli and pumice more or less altered or decomposed. Hence it is now generally believed that the argillaceous matter and most of the other constituents of red clay are derived from the decomposition of volcanic products by the chemical action of sea-water. Pumice and volcanic dust are sometimes ejected in immense quantities during eruptions, and they may be carried great distances from land by currents or winds before they ultimately settle to the bottom of the ocean and form red clay.

Such is the general character of the ingredients in this deposit, but in addition the following usually occur in greater or less abundance in the clay :—

(*a*) *Manganese nodules*, or, more correctly, manganese-iron nodules. In the clay there are found large numbers of the hardest bones of sea-animals, as the teeth of sharks and the ear-bones of whales, some of which belong to species long since extinct, proving the extreme slowness with which red clay accumulates. These bones are sometimes bare, but very frequently they are encrusted with the oxides of manganese and iron, thus forming nodules that often attain the size of a large potato, which they also generally resemble in shape. Such concretions may also form round pieces of pumice or other fragments lying in the clay.

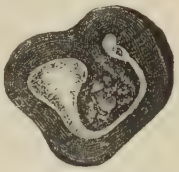


Fig. 90.—Section of a manganese-iron nodule (half actual size). In the centre is the ear-bone of a whale, and it is surrounded by layer upon layer of the oxides. (From the *Challenger* Report.)

(*b*) *Cosmic spherules*. Microscopic examination has revealed that red clay always contains minute specks of the magnetic oxide of iron, in the form of black and brown spherules. The former never exceed $\frac{1}{3}$ of a millimetre in diameter, and the latter are at least twice as large, and there is every reason to believe that the particles are of cosmic or extra-terrestrial origin, in other words, represent the remains of some of the millions of meteors that enter our atmosphere every day.

(*c*) *Zeolites*.—Red clay in certain localities contains perfectly formed crystals of the class of minerals known as zeolites. They are of secondary origin, that is to say, not due directly to the disintegration of pumice, etc., but to the chemical action of sea-water on the volcanic materials.

Distribution of Marine Deposits.—The distribution of the various deposits over the sea-bottom may be seen at a glance in the accompanying map, reproduced from the *Challenger* Reports. A comparison of this map with the one in Fig. 83 shows that the nature of the deposit depends largely on the depth. Proceeding outwards from the coast, we first meet the littoral and shallow-water deposits, and,

FIG. 91.—Distribution of ocean deposits according to the *Challenger* Report.

farther out still, the various muds. About the 100-fathom line blue mud is found. As the sea-bottom shelves down to greater depths, the terrigenous sediments gradually die out, and are succeeded by the organic oozes and red clay. Pteropod ooze does not occur beyond a depth of 1700 fathoms, nor globigerina ooze beyond 2500 fathoms, the calcareous skeletons being, in greater depths than this, dissolved away before they reach the bottom. Indeed, in depths of about 2250 fathoms, the foraminiferal shells begin to appear corroded and rotten, and form a grey marl sometimes called "grey ooze," which gradually assumes a more brownish colour, and passes by almost insensible degrees in the next 250 fathoms into red clay with hardly a trace of carbonate of lime left. Typical red clay occurs at depths of from 2500 to 3500 fathoms; but beyond this depth the relative amount of spicules and hard parts of radiolaria in the deposit gradually increases until, at depths over 4000 fathoms, they are so plentiful (for the sea-water cannot easily dissolve the siliceous skeletons) as to entitle the deposit to be called radiolarian ooze.

A comparison of these ocean deposits with the sedimentary rocks which form so large a part of the earth's crust shows that the rocks are very similar to the shallow-water deposits but not to the deep-sea ones; whence it is inferred that the present oceans occupy depressions which have existed from a very early period of the earth's history, and that the great earth-movements of the past have been confined to the continents and the shallow-water regions by which they are bordered (see also footnote, p. 250).

Questions.

1. Why does an ordinary sounding-line fail to give accurate results when used to measure the depth of the deep oceans? How can correct results be obtained?

2. Why were the old soundings in the deep ocean unsatisfactory? What is the essential principle of the modern apparatus for determining the depth of the ocean? Give a sketch of one of these pieces of apparatus.

3. Describe Lord Kelvin's (Sir William Thomson's) apparatus for determining the depth of the ocean without stopping the vessel.

4. Describe the chief results obtained when a sounding is made in the deeper parts of the ocean.

5. How can the pressure at any depth of the ocean be determined, and what are the chief results obtained?

6. State what you know concerning (*a*) the amount of pressure of oceanic water at a depth of 3000 fathoms; (*b*) the influence of this pressure on the density of the water on the ocean floor; (*c*) the effects produced by this pressure in determining the level of the general surface of the ocean; (*d*) its effect on organisms living on the ocean floor.

7. How have the depth of the ocean, the nature of the ocean bottom, and

the temperature and chemical composition of ocean water at different depths been ascertained?

8. How has the distribution of temperature in the oceanic waters at different depths been determined? What are the chief sources of error in such observations?

9. State what you know concerning the horizontal and vertical distribution of temperature in the waters of the ocean.

10. How have the temperature, the density, and the salinity of the deepest parts of the ocean been determined?

11. What do you know concerning the waters of the deepest parts of the ocean as regards (*a*) temperature; (*b*) density; (*c*) composition; (*d*) the organisms living in them?

12. What do you know concerning (*a*) the temperature of the water at the surface of the ocean; (*b*) the temperature of the water at the bottom of the ocean; (*c*) the minute organisms that live at the surface of the ocean; (*d*) the minute organisms that live on the floor of the ocean?

13. Make a brief statement regarding animal and vegetable life in the ocean.

14. What do you know concerning the animals which inhabit the deepest parts of the ocean?

15. What are the organisms that have the power of separating silica from sea water and fresh water, and what is the nature of the deposits formed by these organisms?

16. State what you know about foraminifera and the part they play in building up rock-masses.

17. Tell what you know about the properties, composition, and origin of glauconite.

18. How are samples obtained from the bed of the ocean? State the nature of the materials found on the deepest ocean-floors.

19. Describe the following: (*a*) globigerina ooze; (*b*) radiolarian ooze; (*c*) diatomaceous ooze; (*d*) red clay; stating in each case under what conditions the materials are found.

20. Describe the distinctive characters of the following materials when studied under the microscope: (*a*) globigerina ooze; (*b*) radiolarian ooze; (*c*) diatomaceous ooze; (*d*) the red clay of the deep oceans.

21. What do you know of the chemical composition of globigerina ooze? Describe as fully as you can the nature of globigerinæ.

22. How are the deposits known as "diatomaceous ooze" and "radiolarian ooze" respectively formed?

23. Tell what you know about red clay.

24. Certain of the constituents of the abysmal clays are said to be of extra-terrestrial origin. Describe such components both as regards their physical properties and chemical composition.

25. Explain briefly the changes which are noticed in the nature of the materials on the ocean floor as we pass from a coast-line to mid-ocean. Account for such alterations as well as you can.

26. Are representatives of the deep oceanic deposits to be found among the stratified materials of the earth's crust?

CHAPTER XIII.

THE INTERNAL HEAT OF THE EARTH, AND SOME OF ITS EFFECTS.

The chief varieties of rocks composing the earth's crust, and the chemical composition, crystalline forms, and physical properties of the most common rock-forming minerals, have been described in the *Elementary Physiography*, pp. 214–241, with sufficient fulness to form the basis of a general knowledge of physiographic geology. We would therefore advise the student to carefully read these pages again at this stage, as they are important and we shall assume a knowledge of them in what follows.

Methods of determining Temperatures at Different Depths in the Earth's Crust.—The thermometers used for the measurement of earth-temperatures are always of the maximum and minimum type, and were described on p. 30.

The rate of rise of temperature in the earth's crust has been carefully investigated by scientists in all parts of the world, and a committee of the British Association, appointed in 1867, presented no fewer than nineteen annual reports on the subject. The methods of observation adopted have been chiefly two :—

I. Observations of temperatures in mines and mountain tunnels.

The chief sources of error to be guarded against in this method are—

(*a*) *Air-currents* affect the temperature of the face of the rock. Ventilation introduces cooler air from the surface, and there are also convection currents due to the radiation of heat from the walls.

(*b*) *Breathing of men and horses* produces heat.

(*c*) *Mining processes* (friction, impact, blasting, etc.) produce heat.

(*d*) *Lights and furnaces* disturb the normal temperature of the rock-surface.

(*e*) *Percolating water*, by its evaporation, will lower the temperature.

(*f*) *Chemical changes* going on in the mine will produce or absorb heat. For instance, rocks with organic matter or pyrites or sulphides readily take

up oxygen, and the heat thus produced is sometimes sufficient to cause spontaneous combustion.

Hence the following precautions are taken to really obtain the normal temperature of the rocks at the given depth. A dry part of the mine is chosen, where it is least crowded and worked, and, as even there the temperature of the air would be misleading, the thermometer is embedded in the rock. In a freshly exposed rock face a hole, AB (Fig. 92), about 3 feet deep is bored, and time allowed for the heat of boring to dissipate. Into this the thermometer T is suspended by a collar, C, for otherwise it might happen to touch a part of the rock at which chemical action was taking place. The boring is then plugged up with wood, D, to prevent circulation of air; pieces of rock are packed against D from the exterior so as to make the whole as like the solid rock as possible.

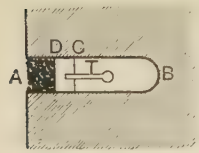


Fig. 92.—Method of obtaining the temperature of the rocks in mines and tunnels.

The imprisoned air assumes the temperature of the rocks around, and after the thermometer has remained in this position for several hours or days it is read, and, if necessary, the mean of a long series of observations is taken.

II. Observations in deep wells and bore-holes. Bore-holes for artesian wells, and those made in the search for coal and other minerals, give valuable information regarding the rate of rise of temperature downwards in the earth's crust.

The chief sources of error are—

(*a*) *The heat due to the friction of the boring instrument* must be allowed time to dissipate. A week is not too much, but the boring operations cannot be suspended so long for this purpose.

(*b*) *Convection currents in the water* which always occupies the tube in a deep boring. Currents of warm water will be ascending and cold water descending, so that the temperature of the water in which the thermometer is standing will not be the same as the rocks round about.

(*c*) *The pressure of the column of water on the thermometer* will make the reading too high unless the instrument is specially constructed.

(*d*) *Chemical action* of the water, or the carbon dioxide dissolved in it, on the minerals will produce heat.

(*e*) *Borings in volcanic regions* are of little value, as the water may be unduly heated.

Hence the following precautions: To protect the thermometer from injury, it is generally enclosed in a copper tube, which opens and shuts at both ends. A geo-thermometer of the kind

described on p. 30 is used—frequently of the overflow type, which is protected from pressure by the hermetically sealed outer case of strong glass. In Germany a plug of wood or clay is driven down to the required depth in the boring; then the thermometer is lowered, and finally another plug. In this country plugs of indiarubber, which tightly fit the bore-hole, are used. They are kept at the proper distance apart by a rod passed through their centres, and the thermometer is attached to this rod between them. When the apparatus is lowered to the required depth, the plugs are, by pulling a cord, made to open out like an umbrella and press against the walls of the boring, and the thermometer registers the temperature of the water isolated in the water-tight compartment thus formed, and this temperature after a time is the same as that of the neighbouring rocks.

Results of the Observations.

1. *The Stratum of Invariable Temperature.*—It is found that at a depth of about 3 feet below the surface diurnal variations of temperature cease, and that the depth to which the annual variation can be traced varies with the nature of the rocks and the latitude, being less near the equator than in higher latitudes. In Java, for instance, seasonal variations are said to penetrate only about 3 feet, whereas at Yakutsk, in Eastern Siberia, the soil is permanently frozen to a depth of 700 feet. In temperate regions the effects of summer's heat and winter's cold cease at about 50 to 80 feet below the surface. Thus in every latitude we come to a zone in which all variation ceases, and the temperature is constantly about the same as that of the mean annual temperature of the place. This zone was called the *invariable stratum* by Humboldt. At Greenwich its depth is 50 feet, and its constant temperature 45°·5 F.

2. *The Rate of Rise of Temperature below the Invariable Stratum.*—Below the invariable stratum the temperature always rises, but the rate of rise varies greatly with locality, ranging from under 30 to over 200 feet per degree Fahrenheit. From the observations made under the auspices of the British Association, Prof. Everett gives the average rate of rise of temperature as 1° F. for every 60 feet of vertical descent below the invariable stratum. Prof. Prestwich has more recently analyzed all available returns for the three classes of observations (mines, tunnels, and boreholes), and deduces a general mean thermometric gradient of 48 feet per degree Fahrenheit.

3. *Irregularities in the Rate of Rise of Temperature.*—There are

variations in the rate of rise of temperature at different depths in the same boring. For instance, in the Grenelle boring at Paris the thermometric gradient at five successive points was 1° F. for 47, 41, 120, 71, 66 feet. In other cases the temperature has remained uniform for some depth, and in others it has actually fallen for a little distance downwards. Still greater divergences occur in the results for different borings.

Examples of a very rapid rate of rise of temperature—

Irkutsk (Siberia), rate of rise of temperature . .	1° F.	for every	11 feet.
Buda-Pesth (Hungary), ,, ,, . .	1° F.	,,	24 ,,
Monte Massi (Tuscany), ,, ,, . .	1° F.	,,	24 ,,

Examples of a very slow rate of rise of temperature—

Calumet and Hecla, Lake Superior, rate of rise .	1° F.	for every	224 feet.
Copper-mines, Mansfield, ,, ,, .	1° F.	,,	219 ,,
Bootle waterworks, Liverpool, ,, ,, .	1° F.	,,	130 ,,

Some of the reasons for the variations observed—

(*a*) Errors of observation, despite all the care taken.

(*b*) The different thermal conductivities and specific heats of rocks pierced by the boring are the main reasons. In rocks which are good conductors or have a small specific heat the rate of rise of temperature is slow, for there is not much difference between the temperatures at different levels. For example, in metallic mines (such as at Mansfield) the thermal gradient is much less than in coal-mines, because in the former case the rocks, being more homogeneous, are better conductors than in the latter in which the heat has to pass from bed to bed in a series of rocks of different kinds.

(*c*) According to the texture and structure of the rocks, they conduct better in some directions than in others. Thus porous rocks are much worse conductors than dense crystalline ones. Again, heat is more easily conducted along than across the "grain," or bedding, or other divisional planes, hence the rate of rise of temperature depends not a little on the inclination of the strata.

(*d*) In almost every boring one or more strata saturated with water are met with, and the presence of water in a rock tends to increase its conducting power, for the interstitial water is a better conductor than air.

(*e*) Although not seen, there may be neighbouring underground springs of warm water, or intrusive sheets or masses of igneous rock that have not yet quite cooled down. Indeed, large subterranean masses of molten rock may take thousands of years to fall to the temperature of the surrounding rocks. Hence there is the quickest rise of underground temperatures in volcanic districts, or those that have recently been so. For instance, Buda-Pesth and Monte Massi are both in regions that have been the scene of volcanic action in comparatively recent times, and the hot springs in the neighbourhood are the residual effects of this volcanic energy.

4. *The Rate of Rise of Temperature in the Earth's Crust decreases*

with Increased Depth.—If the rate continued to be 1° F. for every 48 feet, then at a depth of 30 miles the temperature would be high enough to melt any known substance, and at a depth of 400 miles, the temperature would equal that of the sun itself.

But according to theory, the rate must diminish with depth, for experiments have shown that in a cooling spherical mass the rate of rise of temperature becomes less and less towards the centre. This is borne out by actual observations on the earth. To cite only two examples: in the Grenelle boring at Paris, the rate down to 740 feet was 1° F. for every 50 feet, but between 740 feet and 1600 feet it was 1° for 75 feet; and in the Sperenberg boring near Berlin, which is one of the deepest in the world, the rate down to 1900 feet was 1° F. for 55 feet of descent, and in the next 2000 feet it was 1° for 62 feet.

Geo-isotherms, or isogeotherms, are lines drawn through depths of the earth having the same mean temperature. They are by no means parallel to the earth's surface, nor to the invariable stratum. They are depressed beneath the great ocean floors, because of the ice-cold water there, and they rise towards the surface in land-masses. They are also depressed in polar regions with their thick covering of snow and ice. The perpendicular distance between the subterranean isotherms is an indication of the rate of rise of temperature. If they are far apart the thermometric gradient is slight, and if close together the rate of rise of underground temperature is rapid. For example, under the surface of mountains they are farther apart than usual because of the great amount of radiation from the exposed and relatively large surface, while beneath valleys and under the ocean they are, for the contrary reason, usually more crowded than elsewhere.

Physical Condition of the Earth's Interior.—The fact that, so far as we can observe, there is a more or less regular increase of temperature with depth, necessarily suggests the question—What is the condition of the materials at the earth's centre? To this no definite answer can be given, for the deepest borings extend less than $\frac{1}{4000}$ part of the distance to the centre. The ejecta of volcanoes, geysers, and hot-springs give evidence of the internal heat of the earth, and give us information regarding somewhat greater depths than our own artificial probings. The question as to the physical condition of the parts of the earth deeper than these is a purely speculative one, and therefore unsuitable for discussion

here. We shall therefore merely state the chief theories that have been put forward :—

First theory : That the earth consists of a fluid or semifluid incandescent mass surrounded by a solid shell, which some suppose to be comparatively thin, and others several hundreds of miles thick. Those who support this theory say that the rise of temperature is such that at a certain depth the materials must be fused, and also that we have evidence of this in the molten matter ejected by volcanoes.

There are several serious objections to this theory, but the chief one is that the attraction of the sun and moon would cause tides in this internal ocean, and if the crust were thin ocean tides could not take place, for the crust would rise and fall because of the internal tides, and so, the land and the waters rising and falling together, there could be no sensible tidal movement of the oceans. Lord Kelvin has shown that, on the contrary, the earth is as rigid as if it were a globe of steel of the same size, and that the solid crust cannot be less than at least 2000 miles thick.

Second theory : That as the earth was at one time an incandescent molten mass, it would cool most rapidly at the centre by conduction and at the surface by radiation. Hence there would be a solid central nucleus and a solid shell, and a fluid layer between. Some believe that this has gone on so far that the two zones of solidification have partially united, forming a honeycomb structure, the cavities of which contain the molten lava which gives rise to volcanic phenomena.

Third theory : That the materials composing the earth expand on melting, and if they are not allowed to expand they cannot melt, and that therefore, although the internal portions of the earth are at such a high temperature, still they are solid owing to the tremendous superincumbent pressure. In other words, that the central mass is *actually solid but potentially liquid*, and if by any means there is a reduction of pressure at a place, the white-hot matter is converted into a liquid, and a volcanic outburst is caused.

Which theory is correct we cannot definitely say. The third is the one most generally held by physicists, although there are many geological facts against it. All that we can safely conclude from our present insufficient evidence is that the earth is solid to a great depth, and possibly quite to the centre.

The chemical composition of the earth's interior is, like its physical state, a matter of speculation. We have, however, the following facts to guide us in our inferences :—

1. *The mean density of the earth* is about $5\frac{1}{2}$ times the density of water, while the average density of the materials composing its surface is only $2\frac{1}{2}$ times that of water, from which it is evident that the inner portions of the globe must be of far greater density than its crust. The density at the centre has been calculated to be 10 or 11 times that of water. Some say that, considering the enormous superincumbent pressure, the density of the centre ought to be greater than this, and that there must be an expansive force counteracting to some extent the effect of pressure. This agent they say is heat, and they make the small density of the centre a proof of the internal heat of the earth.

The difficulty to most geologists, however, is not to explain why the density of the nucleus is not greater, but rather why it is so great ; for they maintain that no amount of pressure acting on materials like those at the surface could increase their density to 10 times that of water, and that hence the matter at the centre must be of a denser kind than the crust.

2. *The materials ejected from volcanoes* differ greatly in density and chemical composition from those at the surface. The ultrabasic igneous rocks, for instance, have a specific gravity of over 3, and contain a large percentage of iron and other metals.

Without stating further arguments, we may say that the conclusion to which many geologists have come is that the earth's nucleus contains a preponderance of metallic substances, and that among these iron plays an important part. Some believe that the mineral veins in the fissures communicating with the interior of the globe were filled up from below, and were derived from the metallic centre of the earth.

Volcanoes.—In the elementary treatise we attempted to give a summary of the principal facts relating to the phenomena of volcanic eruptions, the nature of the materials ejected, and the structure and variety of cones. Professor Judd, in his standard work on volcanoes, describes an interesting experiment, due to Mr. Woodward, for imitating on a small scale the mode of formation of volcanic cones composed of scoriæ, pumice, or other fragmentary materials :—

The apparatus (see Fig. 93) consists of a horizontal board with a hole in

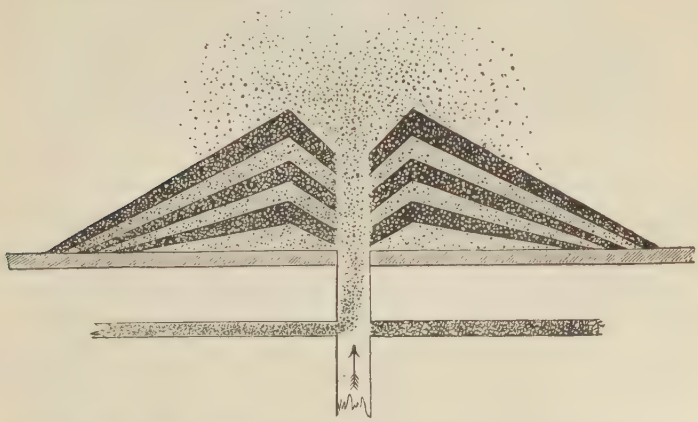


Fig. 93.—Experimental illustration of the mode of formation of volcanic cones composed of fragmental materials. (From *Volcanoes*, by Professor J. W. Judd.)

its centre from which there passes a vertical pipe through which a steady current of air is blown by a foot-bellows. Into this pipe sawdust is introduced along two horizontal tubes leading into it. Then the strong current of air blows the sawdust up the pipe, and causes it to accumulate fastest in a circular heap round the orifice, the diameter of the circle depending on the strength of the blast. As the heap increases, some of the particles slide inwards towards the orifice and others away from it, thus simulating respectively the crater and outward slope of a volcanic cone. By introducing alternately sawdust stained with different colours, the manner of accumulation is better seen, and if a vertical sheet of glass be passed right down through the conical heap, and the sawdust then cleared away from one side of the glass, we see that the coloured sawdust on the other side of the glass has formed layers as in the figure, and that the layers are thickest at the ring of maximum accumulation, and taper from this along both the inward and outward slopes.

An equally simple method of imitating on a small scale the dome-shaped cones of viscid lavas was devised by Dr. Reyer, of Grätz :—

He forced through a hole in a board some wet plaster of Paris. The pasty substance accumulated about the orifice in a rounded heap, and later ejections forced the earlier ones, while still plastic, upwards and outwards. If the successive ejections were differently coloured, then on removing one half of the mound in order to show the internal structure, it was found to consist of concentric onion-like layers, as in Fig. 94.

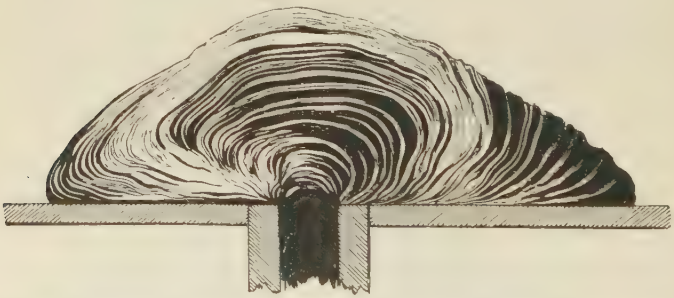


Fig. 94.—Experimental illustration of the mode of formation of volcanic cones composed of viscid lavas. (From *Volcanoes*, by Professor J. W. Judd.)

The Probable Causes of Volcanic Action.—A volcanic eruption consists in the discharge from underground, with greater or less explosive force, of material which is or has been in the molten condition. Hence three things have to be explained, viz. the source of the heat that has melted the material; the force that has raised the material to the surface; and the cause of the explosive phenomena.

1. *The Source of the Heat.*

(*a*) *The Chemical Theory.*—The metals of the alkalies (sodium and potassium) and the alkaline earths (calcium, strontium, and barium) have such a great affinity for oxygen that when they come into contact with water they unite with the oxygen and give off the hydrogen, and at the same time produce a great deal of heat. Hence it was suggested by Sir Humphry Davy, Dr. Daubeny, and others, that if these existed in large quantities far down in the earth's interior, then the access of water and air would cause the oxidation of the metals and the production of sufficient heat to melt neighbouring masses of rock. This chemical theory is, however, unsatisfactory, because the process would be too gradual to account for the enormous quantity of heat, and also, if it were true, immense quantities of hydrogen should be emitted during volcanic eruptions, and such is not the case.

(*b*) *The Mechanical Theory.*—The late Mr. Mallet advocated the theory that the contraction of the earth produces the heat. The internal portions, he said, being at such a high temperature, would be losing heat faster by conduction than the external portions are doing by radiation; hence the central mass would contract more rapidly than the crust, and would shrink away from it. This would cause parts of the crust to crush in, and the friction produced by the crumpling and grinding of the rocks would produce so much heat as to melt some of them.

Many objections to this hypothesis could be stated, but we have space to mention only one, namely, that if the theory were true, then volcanoes should be most abundant in regions where there has been most folding and faulting of the strata, and this is not the case.

(*c*) That the heat displayed in volcanic outbursts is due to the internal heat of the earth, which at a comparatively small depth is sufficient, as we have already said, to melt any rock-materials with which we are acquainted. So far as we at present know, this is the most probable source of the high temperature of volcanic ejecta.

2. *How the Heated Materials are brought up to the Surface.*

(*a*) Water from the oceans which cover three-fourths of the earth, and from lakes, and the surface drainage of the land, finds its way downwards in the earth's crust by cracks and joints and also by capillarity. This water contains various gases in solution, and, when it reaches the heated masses

below, the steam and other gases are absorbed in very large quantities by the incandescent materials because of the high temperature and pressure. The absorbed gases increase in quantity until eventually their tension ruptures the rocks overhead, and forces the lava up the fissure.

(*b*) Other geologists believe that the fissures are produced by the shrinkage of the earth's crust as it cools, and that the lava is then forced up the fissures by the contraction, or merely by the weight of the superincumbent material, and that the explosions only occur by the escape of gases when the molten matter is near the surface.

3. *Origin of the Explosive Phenomena.*

(*a*) They are believed by some to be due to the rocks in the internal portions of the earth being retained in the solid condition because of the enormous pressure on them, although they are at a temperature far above their ordinary melting-point. When the pressure is relieved by the cracking or corrugation of the crust, then the glowing matter suddenly liquefies with explosive violence.

(*b*) The explanation more frequently, however, is that, as the glowing matter was able to absorb great quantities of steam and other vapours because of the pressure on it, then when, for any reason, this pressure is relieved, the gases escape with explosive force. It has often been observed at Vesuvius that after each loud report a huge ball-like mass of condensed steam rises up from the crater, and it can hardly be doubted that it was the sudden escape of the steam that caused the report.

From what we have said, it will be very evident that no complete theory that will explain all the phases of volcanic action has yet been given. It is probable, however, that the main causes have been already surmised, and that several of these are simultaneously concerned in the production of volcanic eruptions.

The Precise Part played by Water in Volcanic Eruptions.—The different theories of vulcanicity centre, as we have seen, round this; hence we shall briefly re-state the views taken:—

1. *Some believe water to be the primary cause of volcanic eruptions*, by large quantities of it finding its way by cracks and joints, and also by infiltration through the pores of the rocks, to the intensely heated matter beneath. The steam thus generated exerts by its expansion such force as to blow out the materials choking the vent, press the lava up the duct, and finally burst with loud explosions in huge bubbles near the surface.

2. *Others adopt the modified view that the percolation of water is one of the contributory causes, but not the primary one.* It is maintained by Professor Judd that an eruption is mainly due to the disengagement of volatile substances actually contained in the volcanic materials, and that water merely affects the fusing-point and therefore the liquidity of the lava, and also doubtless by its expansion and violent escape increases the force of the eruption.

3. *Others take the extreme view that the agency of water is only secondary.* The late Professor Prestwich maintained that water does not cause the volcanic outburst, but that, on the contrary, it is the volcanic eruption that produces the steam by the molten lava in its ascent changing the water lodged around into steam. He asked the question, if the eruption of lava depends on the escape of the absorbed vapour, why are there great flows of lava without a large escape of vapour, or large volumes of vapour given off without lava? He held that the outflow of the lava is really caused by the contraction of the solid crust of the earth upon a hot and yielding interior.

Quiet and Paroxysmal Eruptions.—Some volcanoes are in a state of constant and comparatively gentle activity; many others, again, after continuing in a state of moderate activity or even quiescence for months, years, or centuries, burst into a state of most violent action. Stromboli, which has been constantly active since the time of Homer, is an excellent example of the former class, and Vesuvius of the latter; hence the state of quiet and permanent action is sometimes called the *Strombolian stage*, and the violent and paroxysmal action the *Vesuvian stage;* but we find all gradations between the two, and both stages may be exemplified at different times by one and the same volcano as, for example, Vesuvius, which, after remaining moderately active for generally a few months, suddenly assumes the violent phase. Many other examples of both classes could be given, but we need only mention Cotopaxi as belonging to the Strombolian class, and the volcanoes of the archipelagoes of the Pacific to the Vesuvian.

One of the most violent paroxysmal eruptions on record occurred in August, 1883, at Krakatoa, in the Strait of Sunda, between Java and Sumatra. The cone before the eruption was nearly 3000 feet high, and stood on a little island having an area of 13 square miles. Slight disturbances took place in May, but the terrific explosions began on August 26, were still more violent on the 27th, and practically ceased on the 29th. Places more than 2000 miles away heard the reports. Even at Mauritius, 3000 miles off, they were heard. Fortunately, the island was uninhabited, but when visited next day it was found that half of the cone and about two-thirds of the island had been blown completely away, and where land had been there was in some places a depth of 160 fathoms of sea. A great ocean wave caused by the eruption swept away 36,000 persons

and destroyed about 300 villages in neighbouring islands. Immense volumes of dust were hurled into the air, and Batavia and other towns more than 100 miles away were in complete darkness. The dust was hurled to a height of about 25 miles, and the finer particles were carried by aerial currents more than once right round the globe, causing, while still suspended in the atmosphere, remarkable sunsets in all parts of the world for months after the eruption.

The degree of violence of an eruption depends upon the ease or otherwise of the escape of steam and other gases from the midst of the incandescent liquefied material. Hence it depends upon: (*a*) The viscosity of the lava. If the lava is very liquid, as in the volcanoes of Hawaii, the imprisoned gases easily escape, and the eruption is gentle; and, if viscid, the explosion is more violent. (*b*) The thickness and strength of the superincumbent material; for "to fasten down the safety-valve is obviously as dangerous in a volcano as with a boiler." (*c*) The amount of the water-supply; for this acts not only by the great expansive force of the steam, but also by chilling the surface of the lava and augmenting the tension of the imprisoned gases. The succession of terrific explosions at Krakatoa seems to have been due to inrushes of sea-water acting in this way.

Relation between the Duration of the Repose and the Force of the Succeeding Eruption.—Professor Judd, in summing up what is known on this subject, both from observations of present volcanoes and records of past eruptions, says—

(1) A long period of quiescence is generally followed by an eruption which is either of great violence or of long duration; and, conversely, a very violent or long-continued eruption is usually followed by a prolonged period of repose.

(2) Feeble and short eruptions usually succeed one another at brief intervals.

(3) As a general rule, the violence of a great eruption is inversely proportional to its duration.

Number and Distribution of Volcanoes.—The number of active volcanoes on the surface of the globe is between 300 and 350. If we include extinct volcanoes with cones and craters complete, the number mounts up to nearly 1000; and if we still further include the fumaroles, mud volcanoes, geysers, thermal and mineral springs, and all the other feeble manifestations of volcanic energy, then the number would mount up to many hundreds of thousands.

On the continent of Europe there is one active volcano—Vesuvius,

FIG. 95.—Map showing the distribution of volcanoes.

(there are 6 on the islands of the Mediterranean, viz. Stromboli and Vulcano in the Lipari Islands, Etna in Sicily, Graham's Isle—a submarine volcano off Sicily, and Santorin and Nisyros in the Ægean Sea) ; in Africa, 10 (4 on the west coast and 6 on the east) ; Asia, 24 (12 of them in the peninsula of Kamchatka) ; North America, 20 ; Central America, 25 ; and South America, 37. That is to say, there are altogether about 120 active volcanoes on the great continents, and about twice that number on islands.

The preceding map, and the following brief description will enable the reader to easily grasp the geographical distribution of active and extinct volcanoes :—

A great chain of volcanoes can be traced in the Pacific Ocean, beginning at the New South Shetland Islands to the south of the American continent. From there it passes to Tierra del Fuego in Patagonia, then along the Andes (Cotopaxi in Ecuador being the highest, nearly 19,000 feet), through Central America, and along the Rocky Mountains. In the Aleutian Islands there are twenty-three volcanoes which carry the chain on to Kamchatka on the western side of the Pacific, down which it passes by the Kurile Islands, Japan, Formosa, Philippine Islands, to the Malay Archipelago, where the volcanic activity reaches its maximum. Here we may suppose the chain to divide, one part going north-west through Java and Sumatra and along the eastern side of the Bay of Bengal, the other branch going south-east through New Guinea and the New Hebrides Islands to New Zealand, and thence to Erebus within the Antarctic circle. A branch passes across the Pacific to South America by the Friendly, Society, and Easter Islands. The basin of the Pacific is thus roughly encircled by a great volcanic belt containing fully two-thirds of the total active volcanoes of the globe.

A great belt can also be traced in the Atlantic Ocean, although not so distinctly. It seems to be connected with the submarine plateau running longitudinally down the centre of the ocean, and containing no fewer than forty active volcanoes. We can trace it from the island of Jan Mayen, through Iceland, through the extinct volcanoes of the west of Scotland, to the Azores, Canaries, Cape Verde Islands, Ascension, St. Helena, and the lonely Tristan d'Acunha group. One branch passes to the West Indies which contain six active volcanoes, and another into the Mediterranean where there are, as we have said, seven active volcanoes.

It will be seen at a glance that this distribution of volcanoes can hardly be a matter of chance, and that from it the following general conclusions can be drawn :—

1. Active volcanoes are, with very few exceptions, situated near the ocean or other large masses of water.

2. Volcanoes are mostly distributed along lines or bands, and where they seem to occur in groups this is due to their being arranged either along two or three short lines roughly parallel to each other, or along divergent lines forming a group at their common centre, as in the Italian group.

3. The bands generally coincide either with coast-lines or with great mountain chains (*e.g.* the Andes and Rocky Mountains), or with long submarine plateaux with deep oceanic basins on each side. These bands probably mark lines of weakness in the earth's crust, where the strata are crumpled and folded, and where, therefore, the masses of heated rock below can most readily escape to the surface. Or the reason may in some cases be that the regions we have mentioned adjoin areas of depression, under which the viscid lava is pressed until it finds escape through fissures in the more elevated regions.

Reasons for believing that volcanic eruptions take place along lines of fissure.

1. Fissures have actually been seen to form on Etna and Vesuvius, and eruptions have subsequently taken place at different points along the fissures. For example, a great fissure was seen to open on the slopes of Etna in 1874, and along it thirty-six small scoria cones afterwards formed.

2. A linear shifting of volcanic action takes place, the most probable explanation of which is that after an eruption the orifice gets closed up and strengthened by the solidified material, so that at the next eruption an outlet is forced at another point of the fissure. This linear shifting of volcanic vents is strikingly illustrated at Vulcano, where it has produced a series of partially overlapping cones.

Nowadays volcanic eruptions take place generally at definite points, where cones are formed; but in earlier stages of the earth's history the molten matter seems to have risen up and overflowed all along the fissure, thus forming at the surface great sheets of lava. These are now called *fissure eruptions*.

Thermal and Mineral Springs.—Hot springs abound in regions of active and extinct volcanoes, and doubtless represent one phase of volcanic activity. As an example, we may mention a spring at Abano, in North Italy, about 5 miles from Padua, in which the water has a temperature of 187° F. They also occur in non-volcanic regions, and their high temperature may be due to the water having penetrated to deep-seated strata at a high temperature, and in that case the temperature of the water will depend upon the depth from which it rises. There are famous thermal springs in Germany, at Carlsbad (167° F.), Wiesbaden (158°), and Baden-Baden (153°). In England they occur at Bath, Buxton, Clifton, Matlock, and Ashby-de-la-Zouch. The temperature of the Bath spring is 120° F., and the quantity of water per day is no less than 180,000 gallons.

Springs whose waters contain an unusual quantity of mineral

matter in chemical solution (more than 1 gram per litre) are called mineral springs. They may be warm or cold. Spring water contains carbon dioxide dissolved from the atmosphere and from the air and decaying organic matter in the soil, and for this reason is able to dissolve various mineral ingredients from the rocks passed through, the solution being assisted by the great pressure and, in some cases, by the high temperature of the water. Of course, they invariably contain more than one substance in solution, but they are named according to the predominant mineral; thus—

1. *Calcareous springs* contain carbonate of lime in large quantities, and are, of course, most common in chalk and limestone regions, as for example in Derbyshire, many parts of Italy, and the Auvergne district in France, etc. When the water reaches the surface it gives off the carbon dioxide gas which has enabled it to dissolve the calcium carbonate, which is therefore separated from the water and deposited as travertine. Objects such as moss, twigs, etc., lying in the water get *encrusted* with the calcium carbonate, and hence the springs are popularly known as *petrifying springs*.

2. *Siliceous springs* contain silica in solution, and are much less common, occurring chiefly as geysers in volcanic regions.

3. *Ferruginous or chalybeate springs* contain a large amount of oxide of iron, and are known by their inky taste and the brown or reddish deposit of hydrous ferric oxide they leave along their channels. They occur at Tunbridge Wells, Brighton, etc., and are common in districts where ironstone or rocks with much iron in combination abound.

4. *Brine or saline springs* contain a large amount of sodium chloride in solution, and are common in districts in which rock-salt occurs, as in Cheshire and Worcestershire. A spring in Würtemberg contains as much as 26 per cent. of common salt.

5. Many mineral springs have important medicinal properties, such as (*a*) *chalybeate waters*; (*b*) *muriated waters*, containing common salt as their chief mineral, as for example, Cheltenham; (*c*) *alkaline waters*, containing soda or lime and carbon dioxide, *e.g.* Vichy; (*d*) *bitter waters*, with sulphate of sodium and magnesium, *e.g.* Seidlitz; (*e*) *sulphurous waters*, with sulphuretted hydrogen and sulphides in solution, *e.g.* Harrogate.

Mineral Veins or Lodes are fissures or cracks in the earth's crust which have been filled up with mineral substances. As the fissures, faults, or joints that have been thus filled up are usually vertical or nearly so, the mineral veins generally run nearly vertically through the rocks, and give off branches in various directions. They vary in thickness from an inch up to many feet; and some veins run through the rocks for miles, others for only a few yards.

The chief minerals occurring in them are quartz, calcite, and fluor-spar, mostly in the crystalline condition, and termed *vein-stones*. Parallel bands, or particles, or branching threads of

ores of metals, such as lead, copper, iron, etc., may occur, and occasionally native metals occur, such as copper and gold.

The arrangement of the minerals in a vein is often in double sets of parallel bands, as in Fig. 96. But in other cases, as in auriferous veins of quartz, the vein consists wholly, or almost

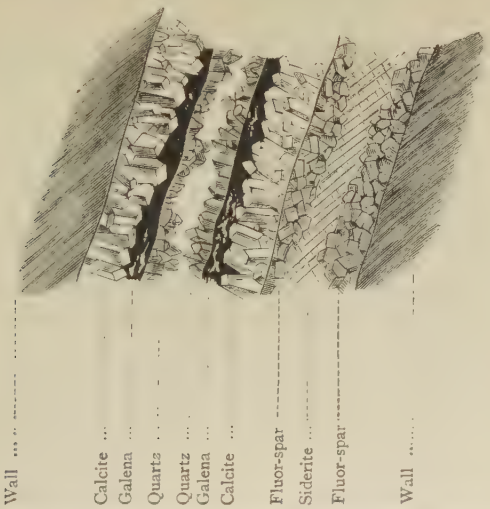


FIG. 96.—Diagrammatic section of a mineral vein. (From Green's *Physical Geology*.)

wholly, of one vein-stone, through which the ore is scattered in minute grains and threads, and the vein-stone has to be crushed in order to obtain the ore by washing.

How mineral veins are formed is still doubtful, but the following are the chief theories :—

1. *That the minerals were formed by lateral segregation*, that is, that they were dissolved by water out of the rocks at the side of the vein, and re-deposited in the vein. In support of this view it is pointed out that the nature of the minerals varies with the surrounding rocks.
2. *That the minerals were brought up from below*, either dissolved in water, or by sublimation (*i.e.* in the form of vapour, and then condensed), or were injected from below in the molten condition.

It is very likely that the minerals have been partially derived from the sides and partially from below, but it seems probable that they come mostly from below, as we have analogous

phenomena going on in hot springs bringing up substances in solution and redepositing them on cooling.

Geysers are thermal mineral springs that, at more or less regular intervals, eject columns of hot water and steam sometimes over 200 feet into the air with a loud roaring sound, whence they derive their name "geyser" from an Icelandic word meaning "the Fury." A geyser consists of a vertical pipe passing down into the earth and terminating at its upper end in a basin or crater at the top of a low cone of siliceous sinter.

Description of Sinter and its Mode of Formation.—Sinter is a rock composed of silica, and formed chemically somewhat as follows: Hot water containing carbon dioxide in solution is able to dissolve potash and soda from granite and other igneous rocks. The water thus becomes alkaline, and is therefore able (assisted by the high temperature and pressure) to dissolve silica out of the silicates in the igneous rocks with which it comes into contact. When the water comes to the surface it cools and evaporates, and therefore deposits the silica as a somewhat porous substance called siliceous sinter, or geyserite. Its usual colour is white or grey, but not infrequently it is some shade of red.

But sinter may not be entirely due to chemical action. Plant-life may assist, for in some cases a very lowly form of microscopic alga (*Isactis plana*) has been found growing in immense numbers in water near boiling-point. They abstract silica from the water to form their skeletons, and hence it is believed that sinter may be to some extent an accumulation of their remains.

On level ground the deposit of sinter round the orifice of a geyser forms a low cone, which may be at most about 15 feet high and 100 feet in diameter; whereas, if the hot spring escapes upon a slope, the deposit of sinter frequently takes the form of successive terraces.

The Phenomena of Geyser Action.—The following description of the Great Geyser, Iceland, may give the reader a clearer idea of the structure and action of geysers generally. During its calm periods it appears a circular pool of water 72 feet in diameter and 4 feet deep, standing in a shallow basin in the summit of a mound of sinter 12 feet high. From the centre of the basin a shaft 9 feet in diameter descends to about 80 feet below the surface. The temperature of the water in the basin varies from 168° to 188° F. "At intervals varying from one and a half hours to half an hour (the intervals becoming shorter as the crisis approaches) there are small explosions and small jets shot up to 20 feet. These intermittent eruptions continue for about a day; then the agitation increases, until with a thundering noise a column of water is thrown up 80 or 100 feet, and this is instantly followed

by two or three jets rising to twice that height." Then no more hot water is ejected for six hours, during which time the tube and basin gradually re-fill.

Distribution of Geysers.—Geysers occur in many volcanic regions, but the best examples are in Iceland, the North Island of New Zealand, and the Yellowstone National Park, Wyoming, U.S. This "park" has an area of no less than 5500 square miles, and was set apart by the Congress as a "pleasuring ground for the benefit and enjoyment of the people." It con-

Fig. 97.—The Giant geyser, Yellowstone Park, U.S.

tains nearly 10,000 hot springs, including 71 geysers, some of which are the most magnificent in the world. The Giantess throws jets 250 feet high at intervals of several weeks; the Giant (Fig. 97) and Castle geysers spout about 200 feet high

at shorter intervals; and Old Faithful (so named from its regularity) throws a column of 150 feet every 63 minutes.

The Cause of Geyser Action.—Many theories of geyser action have been brought forward, but it cannot be said that any one of them satisfactorily explains all the phenomena exhibited. The explanation given by Bunsen from observations of the geysers of Iceland is the one most generally accepted :—

He supposes that the water in the tube communicates by lateral channels or fissures with the subterranean source of the heat. His theory is illustrated by Fig. 98, where the numbers on the right were the actual temperatures observed (in Centigrade degrees) at the different depths, and those on the left are the boiling-points at the corresponding depths, for, because of the increased pressure on the water, the boiling-point rises more and more above 100° C. with descent. It will be seen that the nearest approximation to the boiling-point is at D, where the deficiency is only 2°, and if by the continued inflow of hot water from the lateral fissures this layer be raised to C, it will be 1° above the boiling-point there, and the superheated water will therefore flash explosively into steam and throw the overlying water into the air. This will considerably relieve the pressure on the still hotter water beneath, and will therefore cause a succession of louder explosions and more violent discharges of steam and hot water into the air. These continue until the water left in the tube is no longer above its boiling-point, then the water quietly collects until the conditions are once more suitable for an eruption.

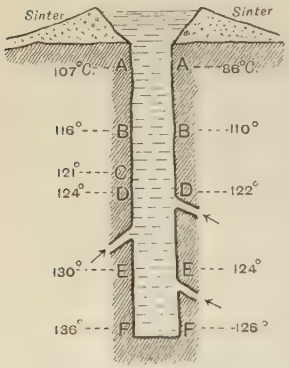


Fig. 98.—Section of the Great Geyser, Iceland, to explain Bunsen's theory of geyser action.

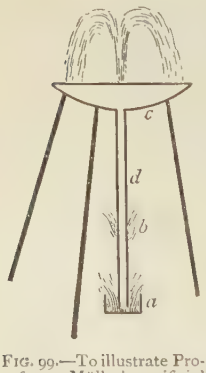


Fig. 99.—To illustrate Professor Müller's artificial geyser.

This action has been imitated by an experiment devised by Professor Müller of Freiburg, and thus described in the *Encyclopædia Britannica:* "If the tube *abd* be filled with water, and heated at two points, first at *a* and then at *b*, the following succession of changes is produced. The water at *a* begins to boil and raises the superincumbent column, so that the water beginning to boil at *b* is raised to *d*, where it is subject to a diminished pressure; it therefore flashes into steam at *d* with explosive force, and the superincumbent water is violently ejected into the air. There it becomes cooled, and falls back into the basin *c*, and thence down the funnel, and the same succession of events takes place again."

From what has been said, it will be seen that geysers bear in many ways a remarkable resemblance to ordinary volcanoes, and might, in fact, be described as volcanoes in which hot water instead of molten lava is ejected by the agency of escaping steam. They occur only in volcanic regions in which the volcanic energy is becoming dormant or extinct. They differ from ordinary hot springs in their eruptive action, and in containing a larger proportion of dissolved silica, but every possible gradation between them is met with.

Questions.

1. (*a*) What special forms of instruments are used for determining the temperature of the earth's crust? (*b*) How are observations on earth-temperatures carried on in mines and tunnels? (*c*) How are observations on earth-temperatures made in bore-holes and wells? (*d*) What are the general results obtained by these observations?

2. Explain the precautions necessary in determining the temperature of the earth's crust at different depths—(*a*) in mines and tunnels; (*b*) in wells and bore-holes.

3. How has the rate of increase of temperature in going downwards in the earth's crust been determined, and what are the chief sources of error in such observations?

4. State what you know on the following points: (*a*) the average rate of the rise in temperature as we descend in the earth's crust; (*b*) the cases of most rapid increase in temperature in going downwards; (*c*) the cases of least rapid increase in temperature in going downwards; (*d*) the increase or decrease in the *rate* of the rise of temperature with depth.

5. What is the average rate at which the temperature changes in descending below the earth's surface? What circumstances may cause variations in the average rate of change?

6. (*a*) Describe a maximum and minimum thermometer. (*b*) State its approximate reading when let down a bore-hole 4000 feet deep; (*c*) at the floor of an ocean 3000 feet deep; (*d*) in a balloon 5 miles high.

7. State and account for the variations in temperature met with on ascending into the air, and descending into the earth and sea.

8. What are geo-isotherms? State what you know concerning the position of those within the earth's crust.

9. What proofs have we of the existence of a high temperature in the interior of the earth?

10. State the chief arguments for and against the following hypotheses: (*a*) that the earth is solid to its centre; (*b*) that the earth consists of a solid shell with a fluid nucleus.

11. Compare the density of the earth as a whole with that of the materials forming its crust, and state the hypotheses which have been advanced to account for the difference which exists.

12. Describe experiments illustrating the mode of formation of volcanic cones composed of fragmentary materials, and of viscid lavas.

13. Describe what is known regarding the action going on within volcanic craters.

14. Give a summary of the chief theories that have been advanced to explain volcanic action.

15. What are the views held as to the part played by water in volcanic eruptions?

16. State examples of quiet and paroxysmal volcanic eruptions, and account for the differences observed.

17. Give an account of the distribution of volcanoes, and accompany your answer with a map-diagram.

18. State the grounds on which it is inferred that volcanic eruptions take place through fissures in the earth's crust.

19. What is meant by *fissure eruptions?*

20. Describe five common kinds of mineral springs.

21. Give a general description of mineral veins, and account for their formation.

22. Explain the action of a geyser, and the cause to which that action is due. Name the principal districts of the globe in which geysers are found.

23. What is the cause of the intermittent action of geysers? How is it that objects thrown down the tube of a geyser will sometimes give rise to an eruption?

24. What is a geyser, and in what respect does a geyser resemble a volcano? State the points in which geysers resemble and differ from volcanoes and ordinary hot springs respectively.

The following are some questions on rocks and minerals fully described in the elementary book.

1. State what you know concerning the crystalline form, chemical composition, physical properties, and mode of occurrence of the following minerals: (*a*) magnetite; (*b*) calcite; (*c*) rock-salt; (*d*) graphite.

2. Give the chief properties of the following minerals: quartz, orthoclase, olivine, augite, and hornblende.

3. Describe the mode of occurrence of the following rocks and the minerals of which each is composed: (*a*) crystalline limestone; (*b*) basalt; (*c*) diorite; (*d*) gneiss.

4. Give the names of the minerals which make up the rocks called "granite," "trachyte," and "basalt," and state what you know concerning the chemical composition of these rocks.

5. Name the minerals which are present in (*a*) hornblende-granite; (*b*) common basalt; (*c*) crystalline limestone; (*d*) hornblende-schist.

6. What minerals are present in granite? In what respect does a granitic rock differ from a lava? What kind of lava has the same chemical composition as granite?

7. State the nature and mode of formation of the substances known as "travertine" and "sinter."

8. Give an account of the manner in which calcareous rocks are formed by the agency of plants and animals.

9. Describe three common types of each of the following: (*a*) volcanic rocks; (*b*) aqueous rocks; (*c*) plutonic rocks, and (*d*) metamorphic rocks.

10. (*a*) State the chief differences in chemical composition of the principal types of igneous rocks; (*b*) how do aqueous rocks differ in composition? (*c*) what is the chemical composition of the chief varieties of metamorphic rocks? (*d*) explain how aqueous rocks may be derived from igneous and metamorphic rocks.

11. Name the corresponding plutonic and volcanic rocks which are of (*a*) acid, (*b*) intermediate, and (*c*) basic composition, stating the minerals which are usually present in each.

12. Compare in general terms the structure of volcanic and plutonic rocks, and account for the differences you name.

13. Give an account of the chemical composition and mineralogical constitution of the chief varieties of lava.

14. What are volcanic dykes? How are they formed? State any peculiarities of their structure with which you are acquainted.

CHAPTER XIV.

MOVEMENTS OF THE EARTH'S CRUST.

Secular Movements of the Earth's Crust.—Owing to the gradual contraction of the earth, its apparently stable and unyielding crust is subject to widespread movements of elevation and depression, and to folding and dislocation of the strata. These movements are so slow that they take vast periods of time for their accomplishment, and hence they are called secular movements (Lat. *seculum*, "a generation, age").

I. Evidences of Elevation.

1. *Raised Beaches.*—We recognize them by the levelness of the ground, the gravel and sand and sea-shells of which it is composed, the water-worn appearance of the boulders with which it may be strewn, and the cliffs with which it may be

Fig. 100.—Diagrammatic section of a raised beach. L, present high-tide level. A, present beach; *a*, old beach; B, modern shingle ridge; *b*, ancient shingle ridge. (From Green's *Physical Geology*.)

backed. In some places the face of the rocks contains sea-worn caves (Fig. 101), and the remains of barnacles have been found attached to the rock, which may also exhibit the borings of marine shell-fish.

The natural inference from all these appearances is that these terraces are ancient sea-beaches, which have been raised above sea-level by a gradual upheaval of the land.

In some cases, raised beaches occur several hundred feet above sea-level. Darwin found them, for instance, at a height of 1300 feet near Valparaiso, and of 1000 feet near Chili. Sometimes there are several raised beaches at successively

higher levels. In some parts of Scotland, for example, a series occurs raised 25, 40, 60, 75, and 100 feet above the existing sea-level; and, indeed, most of the maritime towns and villages of Central Scotland are built upon the first-mentioned raised beach. A succession of raised beaches points to long pauses in the slow upheaval of the land.

FIG. 101.—Raised beach and sea-worn caves at Crail, Fifeshire. (Photograph by G. W. Wilson & Co., Aberdeen.)

Splendid examples of raised beaches occur along the estuaries of the Forth, Tay, and Clyde. We also find them along several parts of the coasts of England (*e.g.* on the shores of Essex, Sussex, Devon, and Cornwall), Wales, and Ireland.

2. *Buildings once close to the sea but now inland from it.* For example, in the island of Crete the remains of harbours and piers that had been built by the ancient Greeks are found 16 feet above the present level of the sea.

3. *Observations based on old tide-marks, or marks placed for the special purpose of enabling measurements to be made of changes of sea-level.* At a part of the west coast of New Zealand, the high-water mark of 1814 is now 200 yards inland.

Very careful observations of the second kind (*i.e.* on marks erected for the purpose) have been made along the coasts of Scandinavia for over thirty years, and these fully demonstrate that in several places, both on the west and the Baltic coast, a considerable rising of the land has taken place during this time,

and that its rate varies in different localities, and in some places is entirely wanting, or even gives place to subsidence.

4. *The stratified or aqueous rocks* composing a large part of the earth's surface have been formed under the sea, as we can tell, not only by their appearance, but by the marine shells and fossils found in them. Fossiliferous beds of chalk and clay are found high up on the slopes of the Alps and far into the interiors of continents.

II. Evidences of Subsidence are more difficult to trace, as they generally get covered up or washed away.

1. *Submerged forests* occur in many regions. In the south of Devon the remains of a forest can be seen in 5 fathoms of water. In the Fen district, around the Wash, and in the Thames estuary, low water exposes roots and stumps of trees. Going still farther back, we have coal-seams (which are ancient submerged forests) far below sea-level, and in some cases actually extending under the sea.

2. *Encroachment of the Sea on the Land.*—Sometimes roads, houses, villages, fields, and even parishes are slowly submerged. Some of the older parts of Kingston, Jamaica, are beneath the sea. The same is the case at Scania, Ystadt, and Malmö, on the southern and Baltic coasts of Sweden.

3. *Fiords.*—The long, narrow, and very deep inlets of the sea known as "fiords" in Norway, and "firths" (the same word) in Scotland, are submerged valleys that were cut when above sea-level by rivers or glaciers, or both. We know this because the glens or valleys extend still further inland, and as this landward part bears distinct evidence of having been formed by the denuding agents we have mentioned, so also we may infer was the lower part of the valley, which has, at a subsequent date, been submerged owing to a subsidence of the land. They are common on the west coast of Norway, Scotland (*e.g.* Loch Fyne and Gareloch), and Ireland (*e.g.* Lough Foyle, Dingle Bay, Bantry Bay).

3. *Coral barrier reefs and atolls* are, according to Darwin's theory of their origin, evidence of widespread depression going on in the beds of the Pacific and Indian Oceans :—

Darwin's Theory of the Formation of Coral Reefs and Islands.—Darwin, while naturalist on H.M.S. *Beagle*, had excellent opportunities of examining reefs, and he found that, while coral fringing-reefs only occur in shallow water, barrier-reefs and atolls sometimes have very deep water on their seaward side, and as coral-polyps cannot live at greater depths than between 20 and 30 fathoms, he concluded that the coral rock must in these cases have been carried down by subsidence of the land.

FIG. 102.—Photograph of a submerged forest at Leasowe, Cheshire (by permission of C. A. Deheux, Esq.) At high water there are about 6 feet of water over the central portion of the forest bed.

He supposed that originally a fringing reef would form round an island, very probably volcanic. Then, as the island slowly sank, the polyps extended upwards at the same rate, but as they would grow most rapidly outwards

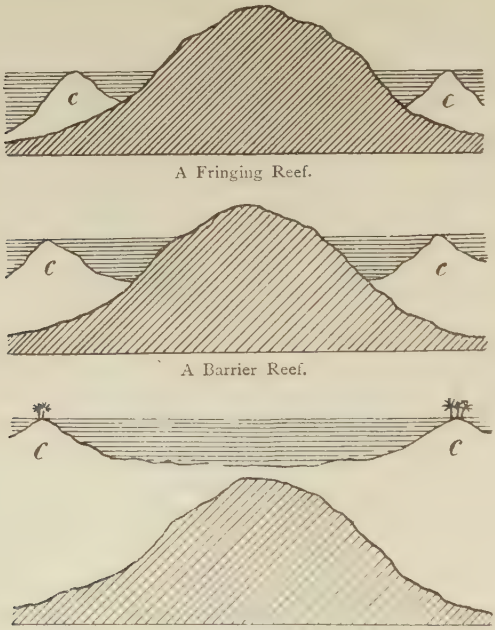


FIG. 103.—Darwin's theory of the formation of coral reefs and atolls owing to the subsidence of the land.

in order to get the best supply of food and oxygen, the distance between the reef and the shore increased, and the fringing-reef became a barrier-reef. Ultimately the island was totally submerged, and the encircling barrier-reef became a circular ring of coral called an atoll.

Murray's Theory of the Same.—(*a*) *Atolls.* Sir John Murray, of the *Challenger* Expedition, has pointed out that many atolls occur where the land is actually rising instead of sinking, and also that if Darwin's theory were correct, then there should be a great depth of coral rock at C in the lowermost portion of Fig. 103, whereas borings show that the thickness is never greater than 120 feet.

He has therefore propounded a rival theory. He maintains that nearly every atoll is built on a submarine mountain. If this is further than 20 fathoms from the surface, then the slow accumulations of skeletons of globigerinæ, pteropods, starfish, etc., will gradually raise it to this height.

Then polyps settle on it, and raise a flat table of coral. As this rises to the surface the polyps grow most rapidly on the circumference, and ultimately the ring rises to sea-level. This ring cuts off the food-supply of the polyps in the interior, and they die out, and their skeletons are gradually dissolved by the carbon dioxide in the water, and so a basin-shaped lagoon is formed.

(*b*) *Barrier reefs*, according to Murray, are formed from fringing reefs without subsidence thus : As the polyps extend seawards parts of the coral are being continually broken off from the outer edge, and as the *débris* gets heaped up in the deep water outside, the polyps settle on it and extend outwards. At the same time those on the inner edge of the reef die for want of food as in the case of the atoll, and their remains are dissolved by the water rich in carbon dioxide derived from the decaying organic matter. In this way the channel is widened, and the reef extends seawards, and the fringing-reef becomes a barrier-reef.

Darwin's explanation is doubtless true in some cases, and Murray's in others, and as the matter is still under investigation it is doubtful which theory is more generally the correct one.

III. Evidences of Alternate Subsidences and Elevations.

1. *The stratified rocks*, which cover so large a part of the surface of the globe, are composed chiefly of marine sediments, with occasional fresh-water and terrestrial deposits. This implies often-repeated oscillations of the crust during the earth's history. Every seam of coal indicates, according to some geologists, a vast subsidence, during which the vegetation got covered up, and then a subsequent elevation for the next growth, and in many cases this must have been often repeated, for in some parts of South Wales, for example, there are as many as 80 seams of coal one above another.

2. *The Temple of Serapis* (so called because some believe it to have been a temple dedicated to the god of that name, but others, a Roman bathing establishment) is a ruin on the coast 7 miles from Naples. It originally had forty-six pillars, but only three remain. About 12 feet from their base each of these is encircled by a broad band 8 feet wide, marked with holes which contain the shells of the molluscs that bored them. Therefore the pillars must have been sunk about 8 feet below the surface of the sea, and then raised above it.

Probable Cause of the Secular Movements of the Earth's Crust.—The warm interior of the earth loses heat faster than the cold exterior, and contracts more rapidly than it; but parts of the latter sink down by their own weight to adapt themselves to the shrinking nucleus, and, owing to the curved form of the earth, sinking in of some parts can only

take place if there is bulging up in others. Thus, if ABCD (Fig. 104) represents a part of the earth's crust which sinks down to A′B′C′D′, then, in crushing itself into the smaller space it will exert great lateral pressure on the rocks at the sides, causing them to be raised in some parts and depressed in others, and also it will itself be thrown into a series of ridges and hollows. We may form an idea of what happens by the following experiment :—

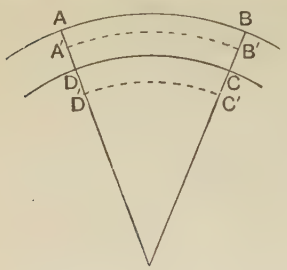


Fig. 104.—To explain the cause of the wrinkling of the earth's crust.

Expt. 37.—Arrange a pile of rectangular pieces of cloth exactly above each other on a table. Place a board or book on the heap, and on this put a 56-lb. weight to represent the pressure of the superincumbent rocks. Place a board or book of suitable size at the two ends of the heap, and

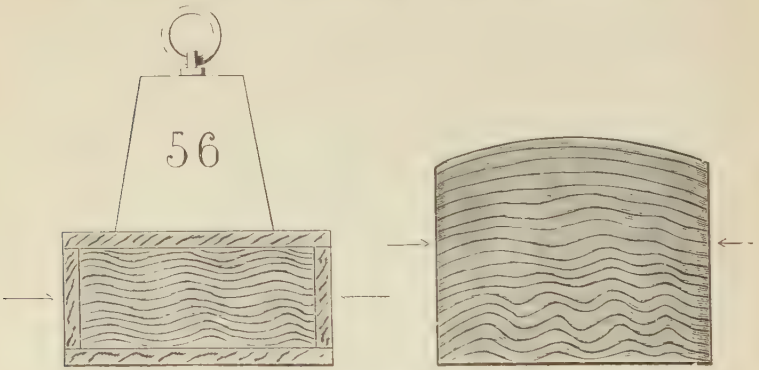


Fig. 105.—Experiment to illustrate the folding of the earth's crust. (Bird's *Elementary Geology*.)

apply lateral pressure by pushing with both hands simultaneously as indicated by the arrows in Fig. 105, and observe the folding of the layers of cloth. The strata A B C D in Fig. 104 would behave in a similar manner.

Disposition of Strata.

1. *Anticlines and Synclines.*—All sedimentary rocks have been originally deposited with their layers horizontal; but owing to lateral pressure produced, as we have explained, by down-sinking of parts of the crust, these originally horizontal

strata get thrown into a series of undulations or folds. If at a fold we imagine a line drawn down through the strata (see the two dotted lines in Fig. 106), then if the strata *incline*

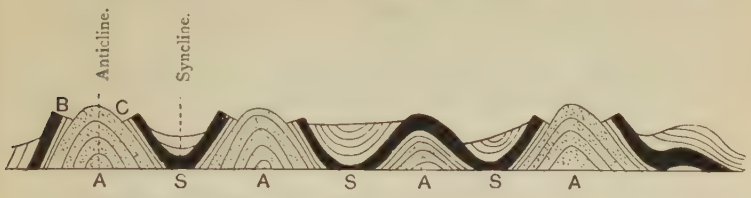


Fig. 106.—Diagrammatic section of the Jura Mountains, showing anticlines (A) and synclines (S).

away from this axis on either side of it, as at A, the fold is called an *anticlinal curve*, or simply an *anticline* (Gr. *anti*, "against, opposite;" *clino*, "I incline"); but if they *incline towards* the axis on either side of it, as at S, the fold is called a *syclinal curve*, or *syncline* (Gr. *syn*, "with or together;" *clino*, "I incline").

The downward inclination of a stratum from the horizontal plane is called its *dip*, and this may have any value from zero in horizontal beds, to 90° in vertical ones.

The place where the edge of a stratum appears or "crops out" at the surface is called its *outcrop* (B and C, Fig. 106).

2. *Faults.*—It frequently happens that during these movements of the earth's crust the strata get broken across, and the parts on one side of the break get upheaved above or depressed below the corresponding parts on the other side. The fissure along which the displacement occurs is called a *fault* or *dislocation*.

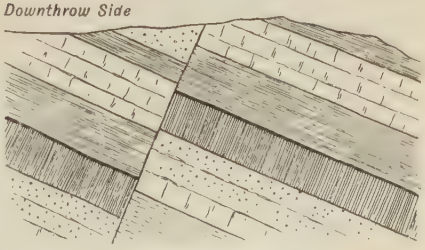


Fig. 107.—A fault.

The side on which the strata are lowest is called the *downthrow* side, and the other the *upthrow* side. As a rule the downthrow is on the side towards which the fault slopes, as in Fig. 107, and this is called a *normal fault*; but in some cases the upthrow is on this side, in which case the fault is called a *reversed fault*.

A fault may run for a few feet or for many miles, and the downthrow

may be a few inches or thousands of feet. For example, a great fault runs across Scotland from Stonehaven, on the coast of Kincardineshire, in a south-westerly direction to the Firth of Clyde, passing through Forfarshire, Perthshire, Stirlingshire and Dumbartonshire, and in Perthshire the down-throw is 8000 feet. A fault runs along the west of the Pennine range for a distance of about 90 miles.

3. *Conformability and Unconformability.*—When each successive stratum rests regularly upon the surface of another

FIG. 108.—Unconformability. The beds of rock (2, 3, 4), belonging to the Carboniferous system, rest unconformably on the denuded surface of much more ancient Silurian rocks (1). (From Bird's *Elementary Geology.*)

the strata are said to be *conformable.* But when one set of beds rests upon the old weathered and denuded surfaces of

FIG. 109.—Double unconformability. The "Whale's Mouth," Cullen, Banffshire (Wilson). C, Tertiary rocks resting unconformably on strata, B, of Old Red Sandstone, which in turn rest unconformably on inclined strata, A, of quartzite. (From Bird's *Advanced Geology.*)

another set, the two series of strata are said to be *unconformable.*

Such an arrangement indicates a great lapse of time, for (*a*) after the lower strata were deposited they must have been raised above the water and been exposed to the weathering and eroding agents; (*b*) they must then have been again submerged at the time the upper series of strata were deposited; (*c*) there must then have been once more an upward movement to convert this deposit into the present dry land. Each of these movements and pauses will represent ages of time.

The Production of Mountain Structures.—According to their geological structure, all mountains may be classified as (1) mountains of elevation, (2) mountains of circumdenudation, (3) mountains of accumulation.[1]

1. *Mountains of Elevation.*—We have already referred to the elevation and folding of the earth's crust along lines of weakness, owing to the great lateral compression produced by the external portions of the globe adapting themselves to the more rapidly contracting hot interior. It is in this way that very gradually, and after an immense lapse of time, a mountain range is formed having the anticlines as more or less parallel mountain ridges and synclines as longitudinal valleys between them.

The Jura mountains between France and Switzerland are a splendid example of a range with anticlinal mountains and synclinal valleys (Fig. 106). Other examples are the Alps, Pyrenees, Cordilleras, Caucasus, and Himalayas.

2. *Mountains of Circumdenudation.*—While typical mountain chains are formed by elevation due to crumpling as explained above, some lower ranges have been formed by the erosive or sculpturing action of rain, frost, running water, etc., as will be described in the next chapter.

An anticlinal mountain is geologically unstable, for rain-water and other denuding agents get easy access to the strata by joints, and also by cracks which will naturally open along the ridge during the folding, and thus the anticlinal arch falls a ready prey to erosion, and its materials are carried down the slopes. In Fig. 106 we see the process already begun. The work of demolition is greatly hastened by landslips, for since the strata dip away from the axis, water that has percolated through the rocks flows along the bedding planes, causing

[1] This is the classification adopted by Professor J. Geikie, F.R.S., in a valuable paper on *Mountains: their Origin, Growth, and Decay* (*Scottish Geographical Magazine*, vol. ii., 1886).

portions of the mountain from time to time to slide into the valleys. For all these reasons, anticlinal strata are worn away

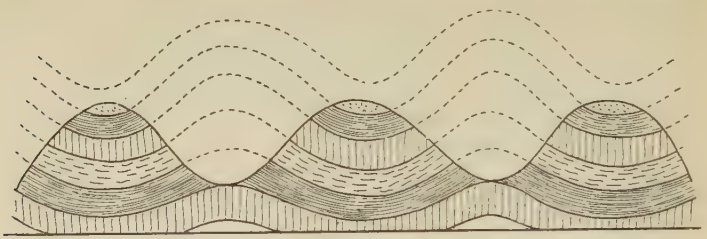


FIG. 110.—Diagram to illustrate how, by denudation in curved strata, the anticlines become the valleys and the synclines the hills or mountains. The dotted lines are intended to represent the strata that have been removed by denudation.

faster than synclinal, so that the anticlines ultimately become the valleys, and the synclines are left standing out as hills or mountains.

Good examples of mountains formed in this way are those of our own islands and of Scandinavia, and the Alleghany mountains (Fig. 111). In these older mountains all unstable

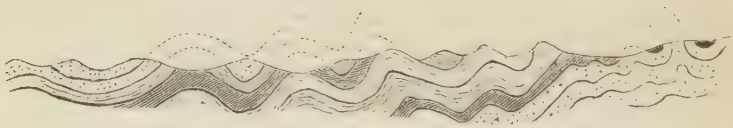


FIG. 111.—Section of the Alleghanies, showing synclinal mountains and anticlinal valleys.

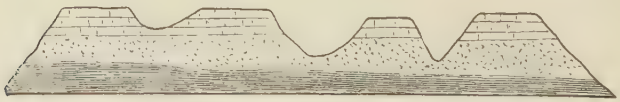


FIG. 112.—Mountains of circumdenudation in horizontal strata.

portions have long ago been removed and landslips are of rare occurrence, while in the younger mountains, such as the Alps, etc., they are numerous and often very destructive.

When the eroding agents carve out valleys in plateaux composed of horizontal or nearly horizontal strata, flat-topped mountains are formed (Fig. 112). The *mesas* or table-mountains of Iceland and Faröe have been produced by circumdenudation in this way.

3. *Mountains of Accumulation.*—Volcanic cones are representatives of this class (Fig. 113).

Seismometry.—Besides the great secular movements of the earth's crust, it is subject to quakings or vibrations called earthquakes. In the writer's introductory book, pp. 248–252, the nature of these sudden disturbances was indicated in a

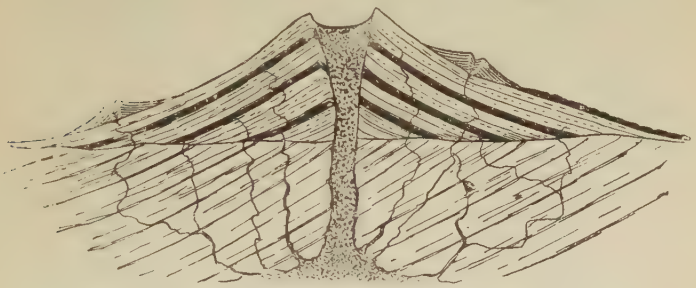


FIG. 113.—Section of a volcanic cone—a mountain of accumulation.

general way. The question naturally arises, Can modern science not do some good, if not by predicting particular shocks, at any rate by lessening their terribly destructive effects in countries in which they are common by pointing out what are unfavourable sites for cities, and how buildings should be constructed to avoid destruction? In order to obtain the knowledge that can be used in this way, it is obviously necessary to find out everything about the movements—their direction, range, period, etc. Instruments used for measuring and recording these are called seismometers. If we can analyze the motion and find out its components in two horizontal directions at right angles to each other, and also the vertical component, then by putting these together we get a knowledge of the whole motion.

A great many different forms of seismometers have been invented, and the recent ones are much more accurate than the older forms, although they still leave not a little to be desired in this respect. Within the scope of this work we can only briefly describe some of the simpler forms of instruments from which satisfactory results have been obtained.[1]

The problem in seismometry is to devise an apparatus in

[1] The most recent information on seismometry is well summarized in *Seismology* by John Milne, F.R.S. (International Scientific Series), 1898.

which a certain point will remain steady during the shock (hence called a *steady point*), and then to this point a light style is attached the other end of which rests lightly on a smoked surface which moves with the quivering ground, and since the style remains steady, the trace made by it is a magnified representation of the motion of the ground; or a common method now of recording the motion is to attach a small mirror to the end of the pointer, and then a ray of light reflected from the mirror on to a sensitive surface which moves with the ground leaves a magnified photographic record of the disturbance.

Horizontal Pendulum Seismometer.—In a very simple form devised by Professor John Milne, F.R.S., and described by him in his book on *Seismology*, the horizontal pendulum P (Fig. 114) consists of an aluminium wire 2½ inches long. At one end of this there is attached a needle-point which rests in an agate cup, C, in a vertical rod attached to the sole of the instrument. The outer end of the pendulum is supported by a silk or quartz fibre attached to the upper end of the same vertical support. In this way P is supported so as to be as independent as possible of horizontal terrestrial movement at right angles to the plane of the diagram, and therefore should such a motion take place during an earthquake the horizontal pendulum will remain undisturbed, just as Foucault's pendulum is unaffected by the rotation of the earth.

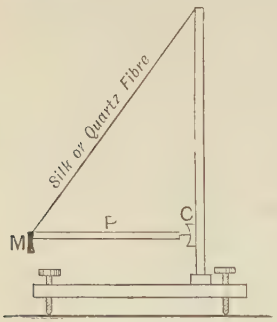


Fig. 114.—Horizontal pendulum seismograph.

To record the horizontal motion of the earth in the plane we have mentioned, there is a small concave mirror, M, at the outer end of the pendulum, on which a beam of light falls from a lamp shining through a vertical slit in front of it. This beam, after reflection, passes through a slit in the horizontal top of a box, inside which there is a photographic film mounted on a cylinder rotated by clockwork which is automatically started by electricity the moment the disturbance commences. The film moves with the earthquake, whereas the mirror is steady for horizontal motion at right angles to the plane of the figure, and hence the tracing on the film will be a record of this component of the earthquake motion.

To get the other horizontal component at right angles to this, an exactly similar instrument is placed with its horizontal pendulum at right angles to this one, and with its mirror immediately above the other, so that a part of the beam of light from the lamp falls on it also, and after reflection produces on the film a tracing near the other one.

The Vertical Motion Seismograph. The most satisfactory instrument yet devised for recording the vertical component of an earthquake disturbance is the horizontal lever spring seismograph. In it the horizontal lever AB (Fig. 115) has its fulcrum at A, where a sharp point projecting

vertically upwards from the lever presses against a part of the frame, as shown in the figure. At the end B of the lever is a heavy weight. The lever is supported at a point C near A by two long spiral springs attached to the top of the frame F. When a vertical disturbance of the instrument takes place during an earthquake, the pull of the springs will vary, but the instrument is so arranged that however much the springs are elongated or shortened from this cause, yet the moment of the upward pull of the springs about the fulcrum A is always equal to the moment of the weight B about the same point, and hence, although the springs are elongated or shortened, the position of B is not thereby affected. B thus remains a stationary point, and can therefore be made to register the amount of vertical motion of the earth during the shock.

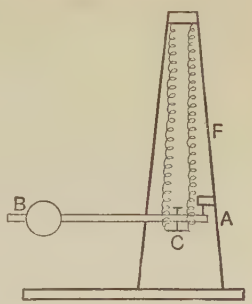


FIG. 115.—Vertical motion seismograph.

Records of the three components of an earthquake disturbance having been obtained, the whole motion can be deduced from them.

Summary of the Chief Characteristics of Earthquake Motions.—1. Recent investigations show that a typical earthquake begins with a series of small tremors unfelt by us, and after ten or more seconds these preliminary tremors are succeeded by a shock, or more usually a series of shocks separated by more or less irregular vibrations. The disturbance then usually dies away even more gradually than it began, the duration of the whole disturbance varying from a few seconds to three or four minutes so far as motion that can be felt by us is concerned; but an ordinary seismograph is disturbed for more than twice that length of time, while a sensitive horizontal pendulum may continue to be disturbed for one or two hours.

2. The range, period, and direction of motion of the particles of the earth's crust are exceedingly variable during an earthquake, and the following statements regarding them are based on Prof. Milne's latest results:—

(*a*) The distance that a particle swings from one side to the other is called the *range* of motion, and the *amplitude* is one-half of this, and may therefore be defined as the distance a particle moves on either side of its position of rest (see p. 46).

The slight preliminary tremors have a range of a small fraction (say about $\frac{1}{10}$) of a millimetre, while the movements constituting the main shock have a horizontal range of motion

varying from a millimetre to a foot, and the vertical range is usually far less than the horizontal, seldom exceeding one millimetre, and in most earthquakes is too slight to be detected.

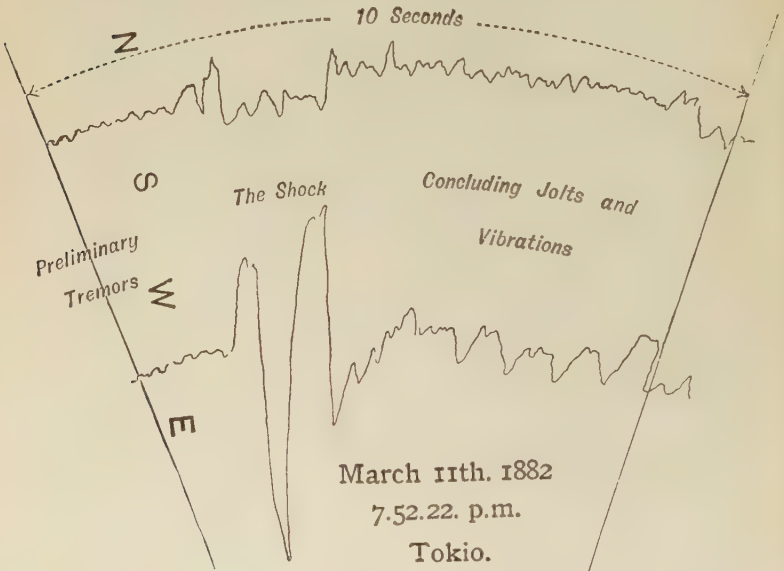


FIG. 116.—A portion of the N.S. and E.W. components of an earthquake as registered on a rotating plate. Observe the preliminary tremors, the main shocks, and the concluding vibrations. (From *Seismology*, by Prof. J. Milne, F.R.S.)

If the horizontal range is 1 or 2 mm., the motion is distinctly felt by us; if it amounts to 10 mm., it is dangerous; while if it is 25 mm., or one inch, it is sufficient to ruin cities. When the range is anything like 9 or 12 inches, it is far too great to be instrumentally measured, and is gauged by the width of fissures in buildings and in the ground strained beyond its limits of cohesion.

(*b*) By the period is meant the time a particle takes to swing from one side to the other and back again. In the preliminary tremors this varies from $\frac{1}{5}$ to $\frac{1}{25}$ of a second; in the movements with a range of 1 or 1·5 mm., which constitute the greater part of the earthquake, the period is about 1 second; while for

motions with a range of 10 or 20 mm. the period is about 2 or $2\frac{1}{2}$ seconds.

(*c*) The direction of motion of the earth-particles during an earthquake may be shown by causing the pointer of a seismograph to record its movements on a smoked plate not moved by clockwork. The result during a severe earthquake may be like Fig. 117. The particle moves first directly outwards and

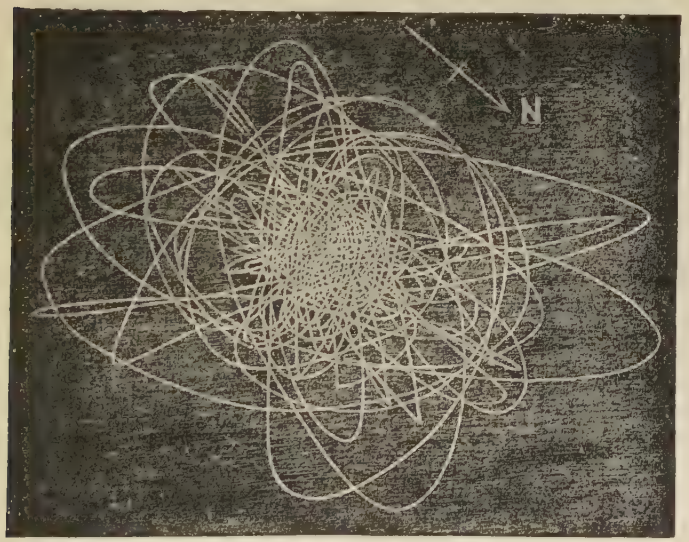


Fig. 117.—Record of the motion of a particle in a great earthquake in Japan, September 3, 1887 (three times actual size). (From *Seismology*, by Prof. J. Milne, F.R.S.)

then inwards in the direction of the shock, and this is the only motion that is well defined, for the particle immediately afterwards begins to move in figures usually roughly elliptical, and inclined at all angles to the first direction, so as to describe a figure sometimes too complicated to analyse, and not unlike a hank of ravelled thread.

(*d*) Seismometers are now part of the equipment of many observatories, so that the time at which the same disturbance reaches different places is known, and then by dividing the distance between two places by the time the disturbance takes to travel from the one to the other we get the velocity of propagation of the earthquake motion in that direction.

Sometimes similar observations are made by means of artificial earthquakes produced by exploding large charges of dynamite or gunpowder in the earth.

There are great differences in the results, but Prof. Milne believes that earthquakes recorded by ordinary seismometers travel for a few hundred miles from the origin at the rate of from 2 to $2\frac{1}{2}$ kilometres (6600 to 8250 feet) per second, and that when better instruments capable of recording earlier tremors have been invented, this may become about 3 kilometres (9900 feet) per second.

The rate of propagation depends on—

(1) The intensity of the shock—the greater the intensity the greater the velocity.

(2) The elasticity of the rocks traversed—the denser the rocks the greater the velocity. For example, the disturbance travels twice as fast through granite as through sand.

(3) The distance from the origin—the greater the distance of a place from the centrum the less the velocity at that place.

Earthquake Waves.—We must not confound the motion of the individual earth-particles with that of the earthquake-waves, any more than we would confuse the motion of the particles of water with the water-waves thereby produced. From what we have said regarding the to-and-fro motion of the particles, it will be evident that the earthquake-waves are in the main longitudinal ones, that is to say, they are waves of compression and rarefaction travelling through the earth's crust, and therefore of the same type as sound-waves in air. When the disturbance reaches the earth's surface it produces long gentle undulations, causing tall objects to rock, and producing in those who experience it a feeling akin to sea-sickness. We have given particulars above as to the velocity of the undulations. Our knowledge of the length of the waves is very imperfect. To our senses the distance between crest and crest appears to be a few tens of feet, whereas, calculating from the velocity, the wave-length comes out from about 400 to 16,000 feet.

Distribution of Earthquakes.—Slight earth-tremors occur in all regions, and old records show that there is probably no country in the world that has not been visited by an earthquake within historic times. The following general statements regarding the distribution of earthquakes may be made :—

1. They are most frequent in localities where slow secular movements of the crust are taking place.

2. Earthquakes are common in volcanic regions.

3. In the New World there is a noted earthquake belt along the west side of the Andes, and severe shocks also occur in the Alleghany Mountains.

4. In the Old World (*a*) an earthquake band stretches from the Azores and

Canaries on the west to Lake Baikal on the east, thus including the countries bordering the Mediterranean in the south of Europe and north of Africa, and northern India, and Thibet. (*b*) There is a district that seems to have Iceland for its centre, and extends to Scandinavia and Great Britain.

5. In Australia there are few earthquakes, and these occur chiefly in the north and west. They are very common in New Zealand.

Causes of Earthquakes.—There are several causes which, either singly or conjointly, are amply sufficient to make the earth's crust quiver.

1. There is little doubt that the majority of earthquakes, and especially all the great ones, are due to secular movements of the earth's crust causing it to be so strained in certain regions that it yields with a sudden crash, and that the series of secondary shocks that follow the main one are due to the grinding together of the fractured strata as they settle down into a position of equilibrium. The fracture in the underlying strata takes place at depths of from 5 or 6 up to 30 miles, and is not generally visible at the surface, but many great earthquakes have been accompanied by the formation of faults extending up to the surface, and this is indisputable proof of the explanation of seismic disturbances just stated. For instance, a terrible earthquake in Japan in 1891 was accompanied by a fault that showed at the surface a downthrow of 20 feet and a length of 60 miles. Similar fracturing of the crust took place in the great Quetta earthquake in the following year.

2. There is no doubt that earthquakes are *sometimes* connected with volcanic action, for—

(*a*) Earthquakes are common in volcanic districts.

(*b*) Before volcanoes break out in a new district there usually is a series of earthquakes, thus giving evidence of ineffectual efforts to establish a vent.

(*c*) Volcanic activity is marked by a sudden decline of earthquake vibrations in the district around, as if a safety-valve had been opened.

(*d*) There are earthquakes after volcanic eruptions have ceased, as if the energy was not now able to force an outlet to the surface.

From such considerations as these, some geologists have concluded that earthquakes are due to exactly the same causes as volcanoes, and that, in fact, all earthquakes are unsuccessful efforts to establish volcanoes. To this view there are, however, serious objections, especially that earthquakes are common in non-volcanic regions, such as Switzerland, the Himalayas, etc., and that even when earthquakes and volcanoes do occur in the same district it is seldom that their foci coincide. We may therefore conclude that, while the subterranean explosions that

accompany volcanic eruptions do undoubtedly cause earthquakes in the immediate vicinity, they could never produce the earthquakes felt over large areas—sometimes right round the globe.

The earth-tremors that are experienced everywhere apart from earthquake shocks may be due to strains of the earth's crust produced by variations of atmospheric pressure (*e.g.* a rise of one inch in the mercury column means that the atmospheric load borne by the earth's surface in that region is increased one million tons per square mile), or to the continual shifting of the load of water with the tides, or to the enormous pressure exerted by winds, especially on mountain ranges.

Questions.

1. Describe a raised beach, and state what inference you would draw from its existence. Name any places where raised beaches are found.
2. How has it been proved that some parts of the land of the globe have undergone elevation in recent times?
3. State the different kinds of evidence from which it is inferred that certain parts of the earth are being upheaved, and others are subsiding.
4. What are fiords, and how do you suppose them to have been formed?
5. How, according to Darwin, have atolls been formed, and what is Murray's explanation of the same?
6. How have the great movements of the earth's crust been brought about? What has been the result of these movements on the structure of the rocks?
7. Explain the terms "anticline," "fault," "downthrow," "unconformability," and point out how each is caused.
8. How do you account for the fact that, although stratified rocks were originally horizontal, or nearly so, they are rarely found horizontal now?
9. Point out the operations and forces at work in the production of (*a*) folded mountains; (*b*) mountains of accumulation; (*c*) mountains of circumdenudation.
10. Describe the structure and mode of origin of mountain chains of "the Appalachian type."
11. Explain the following terms: (*a*) seismograph; (*b*) rate of propagation of the earthquake wave; (*c*) seismic vertical; (*d*) coseismal lines.
12. What are seismometers? Describe some form of seismometer with which you are acquainted.
13. How has the rate of propagation of earthquake vibrations been determined? What do you know concerning the results arrived at?
14. What are the chief causes which have been suggested as giving rise to earthquake vibrations?
15. What is an earthquake? How is it caused? Tell what you know about the distribution of earthquakes.

CHAPTER XV.

EARTH-SCULPTURE.

Denudation.—When the materials have been uplifted by the subterranean agencies treated of in the last chapter, at once they begin to be slowly sculptured by nature's great carving tools—air, rain, snow, frost, glaciers, rivers, and the sea—and it is upon their action that the scenery of a country depends. The destruction and removal of rock-materials so as to expose parts previously covered go by the general name of *denudation* (Lat. *denudo*, "I lay bare"), while the destructive action of the four atmospheric agencies mentioned above is called *weathering*.

Denudation is generally divided into (*a*) atmospheric denudation, or, since it takes place beneath the atmosphere, sub-aërial denudation, in contradistinction to (*b*) marine denudation, which takes place under water. Hence we have

Atmospheric or *sub-aërial denudation*, due to the action of	A. Air. B. Rain and snow. C. Frost. D. Streams and rivers. E. Glaciers.
Marine denudation, due to the movements of the sea, viz.	Waves and breakers. Currents. Tides.

A. **Air** is an important agent in modifying the whole of the land-surface of the globe. It acts chiefly in three ways—

1. *Chemically.*—The oxygen, carbon dioxide, and other constituents of the air bring about important chemical changes in the minerals of the crust, but as it is rain that introduces them into the rocks, we shall defer the study of their action meanwhile.

2. *Changes of Temperature.*—The rocks are heated by the sun during the day, and at night they are cooled by radiation.

There are also annual variations of temperature. The alternate expansions and contractions thus produced in course of time crack the hardest rocks and loosen fragments at the surface.

It is in regions with a dry atmosphere, such as mountain-peaks or some tropical regions, that the surface is most heated by the sun during the day, and most rapidly cooled by radiation at night. Dr. Livingstone found, for instance, in the region of the Zambesi to the west of Lake Nyassa, that during the day the rocks were heated up to 137° F., and during the night cooled so rapidly that they gave off, with a loud crackling noise, fragments weighing from a few ounces up to 200 lbs.

3. *Wind.*—Air in motion is a powerful agent in eroding rocks. It sweeps away the particles loosened from rocks, and exposes a new surface to the disintegrating agencies. Also the gritty particles of sand driven in clouds by the wind against bare rock-faces wear them smooth and carve them sometimes into curious forms. The wind likewise piles up great sandhills or "dunes" along broad sandy shores and in deserts. In the Sahara they are sometimes over 600 feet high.

B. **Rain** is the most important of all the agents employed in the disintegration of rocks. Its action is twofold—chemical and mechanical. It chemically dissolves out the soluble ingredients in the rocks into which it sinks, and it mechanically washes away the loosened materials.

1. *Chemical Action of Rain.*—Rain-water, in its passage through the air, dissolves out of it a certain amount of oxygen, carbon dioxide, and other acid gases. Also as the water passes through the soil it dissolves more carbon dioxide and likewise certain organic acids (the humus acids) produced by the life and decay of organisms there. The rain-water, charged with these, sinks deep down into the pores and fissures of the underlying rocks, and exerts a powerful solvent action. Limestone is readily dissolved by it, and caves are hollowed out in which stalactites and stalagmites are formed.[1] Granite, gneiss, basalt, and other rocks containing felspar have that mineral dissolved out of them, and deposits of clay are formed.[2] Also, the oxygen dissolved in the water oxidizes minerals that can unite with more of that element. In this way rocks that contain iron become brown or reddish when weathered; it is simply a case of the rusting of those minerals. Insoluble sulphides (*e.g.* sulphide of iron) become oxidized and changed into soluble sulphates, causing the rock to be disintegrated. We need not further multiply examples of the chemical action of rain.

[1] See *Elementary Physiography*, p. 219. [2] *Ibid.*, p. 238.

2. *Mechanical Action of Rain.* — When a rock has been disintegrated by weathering, the particles are washed off by rain and carried to lower levels. But rain acts mechanically also in overcoming the force of cohesion in softer rocks by its continuous battering. Every one will have noticed, for example, the indentations made by heavy rain in mud and sand. When rain falls on beds of stony clay or other soft rock, then the softer materials are washed away, but the stones protect the parts beneath them, which thus form pillars, each surmounted by a stone. Examples of those *earth-pillars* occur in our own and various other countries; in the Sawatch district of North America they reach a height of 400 feet, and these are the highest known.

C. **Frost.**—Rain and melted snow make their way into the pores and joints of rocks, and if the temperature subsequently falls below 32° F. the water freezes, and in doing so expands and ruptures the rock, and the loosened fragments fall off when the thaw comes. The destructive action of frost is greatest in high latitudes and altitudes—that is to say, in polar and in mountainous regions. For example, in Greenland and Spitzbergen great destruction is wrought by frost. During the short warm summer the snow melts and fills the pores and crevices of the rocks with water, which afterwards freezes and splits off large pieces of rock. Similarly on mountains.

D. **The action of rivers** is partly chemical, but mainly mechanical, and consists (1) in transporting materials from higher to lower levels; (2) in eroding their channels; and (3) in depositing the materials to form new sedimentary deposits along the sides of the rivers, and at their mouths, and along the coast on either side of their mouths. The first two divisions constitute the destructive or denuding action of rivers, and belong, therefore, to this chapter; the third is their constructive action, which was treated with sufficient fulness in the *Elementary Physiography*, pp. 202–205.

1. **Transportation of Rocky Materials Seawards.**

(*a*) *In Chemical Solution.*—The amount and kind of material held in solution varies with the geological character of the river-basin. Thus the Aberdeenshire Dee flows through a granitic district, and an analysis of its water above Balmoral only gave 1·06 grain of dissolved matter per gallon. On the other hand, the Thames at Kingston contains more than 19 grains per gallon, and multiplying this by the number of gallons that pass there in a year, it is found that this river removes from

the land no less than 587,000 tons of material in solution, about two-thirds of which is calcium carbonate. Similarly, the waters of the Danube remove $22\frac{1}{2}$ million tons, and the Mississippi no less than 150 million tons in solution per annum. These figures will suffice to give the student an idea of the enormous destructive work performed imperceptibly and incessantly by all the rivers of the world.

(*b*) *In Suspension.*—Winds or rains are constantly sweeping particles of rock or soil into streams. The solid particles, although heavier than the water, are prevented from sinking by the motion of the water, and are said to be carried along in suspension. It is the material in suspension that causes the muddiness of river-water, and after heavy rains the turbidity is increased because more particles are washed into the river, and also because the increased volume and velocity of the current enable it to carry along larger particles.

The chief substances carried by rivers in suspension and solution are stated in the elementary book, p. 105.

(*c*) *By rolling and pushing along the bottom gravel and stones* too large to be held in suspension.

The ability of a river to transport solid materials by the methods (*b*) and (*c*) depends upon the volume and velocity of the water, and upon the specific gravity and shape of the particles, for, of course, rounded stones are more easily pushed forward than others. It has been calculated that the transporting ability of running water is as the sixth power of its velocity, so that if the rate of the current be doubled during a spate, then its transporting power will be increased 2^6, or 64 times; therefore if a river can ordinarily just transport materials not heavier, say, than an ounce (a velocity of about two miles an hour is sufficient for this), it will be able when in flood to move along stones weighing 4 lbs.

The amount of solid matter carried by a river by the methods (*b*) and (*c*) is much greater than the quantity in solution. To give but one illustration, it has been calculated that the Mississippi annually discharges 363 million tons of material carried in mechanical suspension, in addition to 21 million tons pushed along the bottom to the sea.

How to calculate the amount of solid matter carried along by a river both in suspension and solution: A gallon of water may be taken from the river at a certain point. Filter it, and thus obtain the weight of matter in suspension per gallon. Then slowly evaporate the filtered water, and weigh the solid residue left; this is the weight of matter in solution per gallon. Next, to find the volume of water that passes in a year, the area of cross-section of the river at the place is obtained by careful soundings, and this

is multiplied by the length of water passing the place during the year (found from the average rate of flow of the river). This volume can easily be reduced to gallons, since a cubic foot of water measures 6·23 gallons.

Now add together the weights of solid matter in suspension and solution per gallon, and multiply their sum by the number of gallons of water passing the point in a year, and the product will be the weight of material removed by the river from the land per annum.

From calculations of this kind, it appears that, in order to lower the average level of their basins one foot, the Mississippi must work for nearly 6000 years, the Rhone for 1500 years, and the Po for only 700 years; and Sir John Murray estimates that to reduce all the dry land of the globe to sea-level, the rivers would require to work at their present rate for six million years.

2. **Erosion of River-beds.**—Rivers are constantly deepening and widening their channels, not so much by the friction of the water as by the rubbing of the earth and stones carried along by the current against the bottom and sides. The erosive power of a river will therefore, like its transporting power, depend almost wholly on its rapidity.

Where there are eddies in a river, the fragmentary materials carried by it are swirled round and round, and in course of time drill out more or less circular steep-sided cavities called *pot-holes*.

The steepness of the sides of river-valleys depends upon (*a*) the nature and arrangement of the rocks; (*b*) the relative rapidity of the deepening action of the river and the weathering action on the sides of the valley by rain, frost, etc. When weathering is the more rapid, the valley is wide and shallow, and has gently sloping sides; whereas when river-erosion is the more rapid, the valley is narrow and deep and the sides nearly perpendicular. Such a river gorge is called a *cañon*.

In no part of the world are more magnificent examples of cañons to be found than in the portion of the western territories of the United States watered by the Colorado and its tributaries. The cañon region is almost rainless, and is an elevated tableland consisting of horizontal layers of limestone and sandstone. The Grand Cañon is 300 miles long, varies from 3000 to over 6000 feet deep, and in most places is from 150 to 500 yards wide. At the bottom of this chasm runs the Colorado River, and joining it are similar ravines formed by the tributary streams.

The chief causes of the cañons are—

(*a*) The dryness of the climate, so that the weathering action of rain and frost is very slight.

(*b*) The strata are nearly horizontal (Figs. 118 and 119), and the joints are vertical, so that even if a part falls off owing to atmospheric denudation, the face of the cliff is still nearly perpendicular.

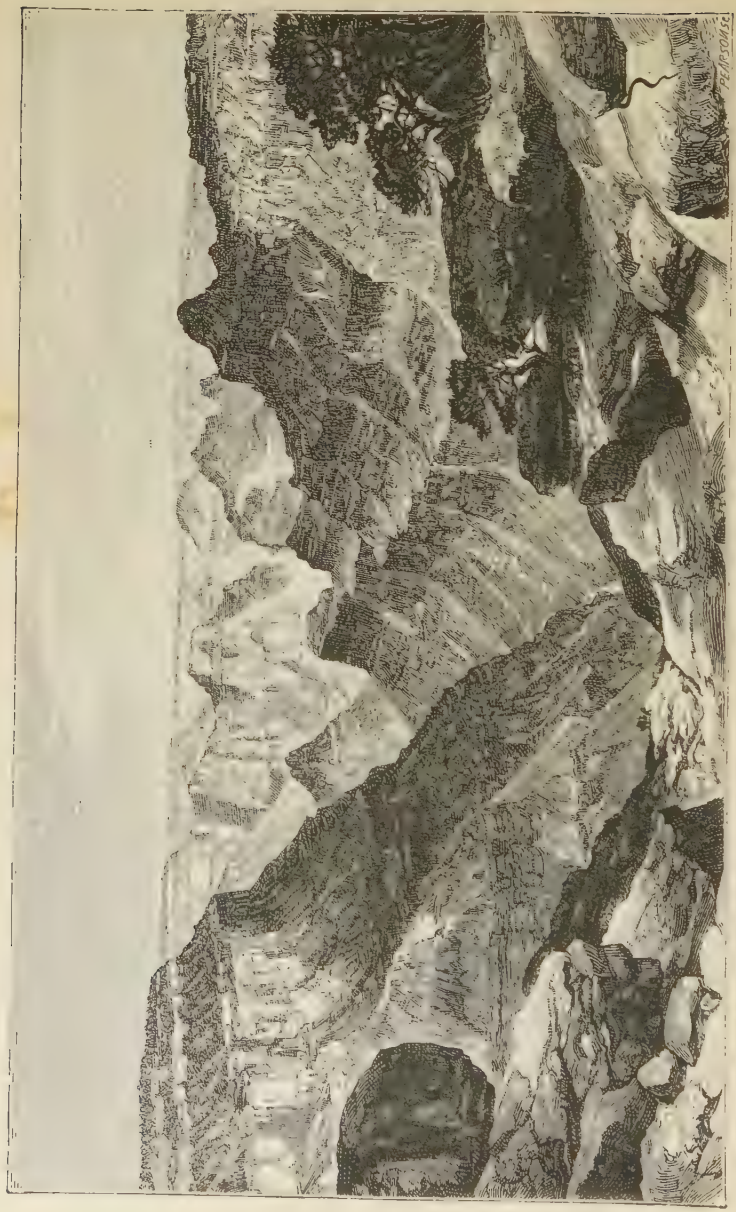


FIG. 118.—Scene in the cañon region, Colorado. (Longmans' *School Geography.*)

When a river-bed consists of rocks of different degrees of hardness, the softer rock is, of course, eroded more rapidly than the hard one, and a cascade or waterfall is in course of time formed over the hard ledge of rock. For example, the Niagara Falls, midway between lakes Erie and Ontario, have been formed by the river flowing over thick beds of limestone beneath which are beds of soft shale (Fig. 120). The limestone ends in steep cliffs at Queenstown, 7 miles further down the river, and it is there that the falls must have been originally formed in the manner described above. They have slowly retreated up-stream to their present position, because the soft shale is being crumbled away by the dash of the spray in the pool at the bottom of the falls, and thus the limestone is undermined, and parts of it fall every now and then.

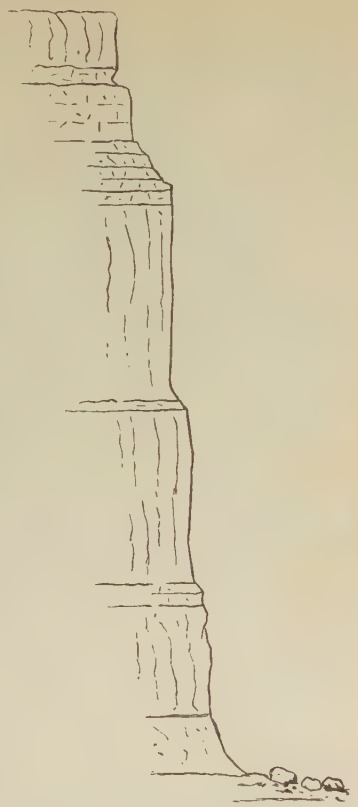


FIG. 119.—Section of one of the sides of a cañon in the Colorado region, showing the horizontal strata and perpendicular face. (Bird's *Elementary Geology*.)

The falls are said to be moving up-stream about 4 feet per annum, and at this rate they would require

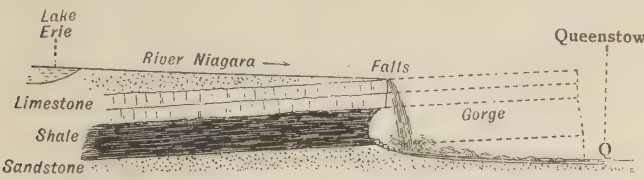


FIG. 120.—Section of the rocks at the Falls of Niagara. The dotted lines represent the continuation of the strata along one side of the gorge to Queenstown.

about 10,000 years to recede from Queenstown to their present position. The magnificent volume of water pours itself over a cliff 165 feet high. The ravine, 7 miles long, cut by the river in the hard limestone has a width of from 200 to 400 yards, and its almost perpendicular walls are from 200 to 300 feet high.

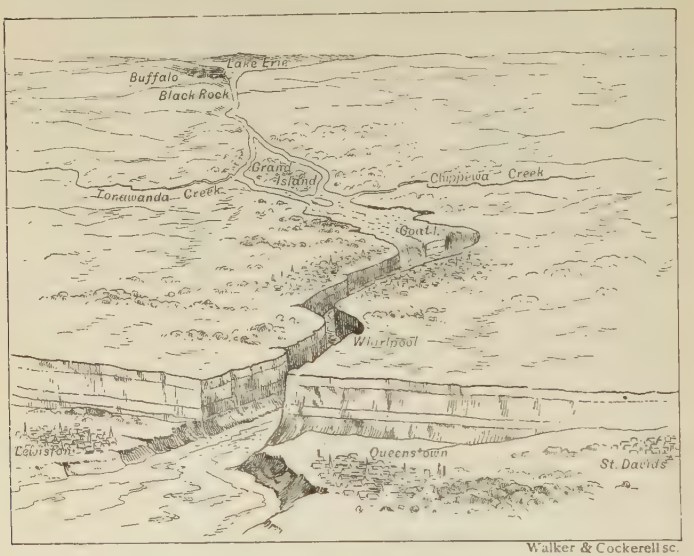


FIG. 121.—Bird's-eye view of Niagara Falls and River.

E. **Action of Glaciers.**—The geological work of glaciers is solely mechanical, and consists (1) in transporting rock-*débris* to lower levels, and (2) in erosion of their channels.

1. *Transport of Rock-débris.*—Rocks, earth, etc., loosened by the various weathering agents, but especially frost, fall down the rocky slopes on to the surface of the ice, and are carried along by it as the lateral and medial moraines. Sometimes portions of the superficial *débris* are engulfed in crevasses, and are carried downwards enclosed in the ice. Moreover, a glacier pushes along underneath it a considerable amount of detritus, which has found its way there by falling down crevasses extending through the whole thickness of the glacier, or has been torn by the ice from the bed over which it moves. When the ice melts, the rubbish is deposited in a confused heap of earth and stones called the terminal moraine. Should the

glacier reach the coast, it gives off icebergs, which carry their load of rocky material out to sea, and there deposit it as the ice slowly melts.

2. *Erosion of the Beds of Glaciers.*—The slow yet incessant movement of a glacier, and of the fragments of rock forced along underneath it, has a grinding action on the rocky bed, smoothing it and removing irregularities just as if it had been subjected to the action of a file. The action of glaciers and ice-sheets in scooping out hollows, and thus giving rise to lakes, has already been referred to on p. 153.

A slight idea of the great amount of erosion unceasingly effected by glaciers is given by the quantity of sediment carried by the rivers formed by their melting. The milky appearance of these glacial rivers is due to fine, almost impalpable, powder carried along by them in suspension. The Aar glacier is by no means one of the largest in Switzerland, and yet it has been estimated that the river issuing from it carries in suspension 280 tons of fine particles per day in summer, in addition to the coarser material pushed along the river-bed.

Evidences of Past Glacial Action.—Although glaciers are no longer found in this country, yet there is abundant proof that at one time the climate of the northern hemisphere was much colder than at present, and that our islands (except the part south of the Bristol Channel and the Thames) and the northern parts of Europe and America, were enveloped in snow and ice just as Greenland is at the present day. The chief evidences of these ancient glaciers and ice-sheets are—

1. *Deposits of morainic matter* typically represented by mounds or ridges of sand, gravel, and boulders. These often run like ramparts across the mouths of mountain valleys, and are the remains of the terminal moraines of the glaciers that at one time crept down them. In many of our highland glens a succession of these occurs, and marks the retreat of the glacier with the gradual return of more genial conditions.

Large portions of our islands, as well as the northern and middle parts of Europe and North America, etc., are covered by a stony clay formed by erosion underneath the sheets of ice that moved over these regions. This deposit is known as *boulder-clay*, or *till*. It is a stiff clay containing smooth and finely scratched stones or boulders scattered irregularly through it. The particles of the boulder-clay have been formed by the grinding action of the ice on the rocks beneath. In other words, this deposit is just the *bottom-moraine*, or *moraine profonde*, of the glacier or ice-sheet.

2. *Erratics and Perched Blocks.* These are pieces of rock, sometimes of immense size, perched often in precarious positions on hilltops and steep mountain slopes. They are frequently not of the same kind of stone as the district in which they are found, and have been transported thither by moving ice and deposited as the ice melted. We find them in many parts of our islands; *e.g.* "Samson's putting-stone," west of Callander, Perthshire,

weighs 40 tons. One found near St. Petersburg weighed 1500 tons, and had been transported 35 miles by the ice.

3. *Smoothly rounded Rocky Knolls.*—One of the most notable features of a country that has been subjected to glacial action is the long flowing

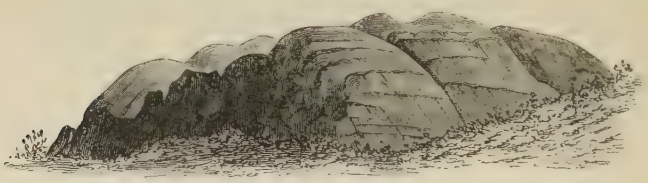


FIG. 122.—Roches Moutonnées. (From Green's *Physical Geology*.)

outlines of its hills and valleys. This is due to the ice grinding the corners of the rocks and bevelling off all irregularities. Small dome-shaped hummocks produced in this way sometimes have at a distance the appearance of a flock of sheep lying down, and hence have been named *roches moutonnées*, or sheep-rocks (Fig. 122).

FIG. 123.—Perched blocks and striated rocks, Glacier Garden, Lucerne.

4. *Polished and Striated Rock Surfaces.*—The scratches or striæ are more or less parallel, and from them we can tell the direction in which the ice

moved. We meet with examples in a great many parts of the country, such as the neighbourhood of Edinburgh, and in the mountains of Cumberland and Wales.

5. *Glacial Lakes* (see p. 153).

Soil.—If we examine an excavation made into the earth's crust, or a section exposed along a river-bank or railway cutting, we see that at a greater or less distance below the surface there is solid rock, and above it broken-up fragments of the rock, and at the surface a much darker layer consisting of much finer particles and generally full of rootlets (Fig. 124). This surface layer is called the *soil*, and the layer of larger fragments below it the *subsoil*. Hence *soil is the superficial film of the earth in which vegetation grows. It varies in thickness from one or two inches to several feet, being thinnest on hillsides and thickest on level ground. It consists of disintegrated particles of rock mixed with varying amounts of decaying organic matter to which its dark colour is due.* The nature of the soil depends on that of the subsoil, and this in turn on the rocks beneath. The gradual transition from the rocks upwards shows that the soil is formed by the breaking up of the rocks by the various weathering agencies—air, changes of temperature, rain, and frost—assisted by plants and burrowing animals, such as the mole, rabbit, and particularly the earth-worm. Plants aid in the demolition of rocks by forcing their roots into crevices and wedging the parts asunder, and also the organic acids obtained from the decaying vegetable matter greatly increase the solvent power of the percolating water. Earth-worms assist in the formation of soil by dragging decaying vegetation into their burrows, and by swallowing the earth for the sake of the nutriment it contains, and then ejecting the non-nutritive earth at the surface in the form of worm-casts

FIG. 124.—Section showing the gradual transition from rocks beneath to soil at the surface. *a*, the soil consisting of fine particles; *b*, the subsoil consisting of larger pieces gradually increasing downwards; *c*, the rock with cracks called joints. (From Longmans' *Geographical Series*.)

i.e. worm-like coils of fine mould. It was Darwin who first pointed out the importance of worms in this respect. He calculated that there are on an average more than 53,000 worms in an acre of good soil, and that these pass through their bodies and bring to the surface 10 tons of soil per annum.

The Action of Springs.—The water that sinks into the ground, and after a longer or shorter journey returns to the surface again in springs, is employed by Nature as one of her sculpturing tools. Its work is twofold—chemical and mechanical.

1. *Chemical Action of Springs.*

(*a*) *Solution.*—As was already fully explained in Chapter XIII., spring water removes in solution many of the constituents of rocks, which thereby undergo extensive alterations in structure and composition. In this way subterranean tunnels, channels, and caverns are made in the earth's crust, especially in limestone regions, such as Derbyshire and other parts of our own islands. One of the most extensive limestone caverns in the world is the Mammoth Cave in Kentucky, which has over 150 miles of passages.

(*b*) *Deposition.*—Limestone grottoes are sometimes very picturesque because of the stalactites and stalagmites in them assuming all sorts of delicate and fantastic forms. Also, at the orifice of mineral springs there are great deposits of travertine, sinter, and other minerals, sometimes forming cones, terraces, and natural bridges. The Bath wells alone deposit yearly over 600 tons of solid matter, chiefly the sulphates of calcium and sodium.

2. *Mechanical Action of Springs.*—As underground water passes through the interstices and fissures of rocks it loosens and removes particles; but its most important work is in causing large portions of the rocks to become detached and slide down to a lower level. Such movements are called *landslips*. Thus, if water soaks through the earth till it comes to an impermeable stratum, it will lubricate the latter and loosen the cohesion between it and the layer above, and then, if the slope be suitable, gravity will cause the upper layers to slide downward. Landslips are,

FIG. 125. To illustrate how springs may cause landslips. The water flowing along the surface of the impermeable stratum of clay may cause the stratum above to slide down as a landslip.

however, sometimes due to frost rupturing the rocks by the expansive force of the water, and causing them to fall when the thaw comes. Earthquakes also often send down strata lying in unstable positions.

Small landslips are common on all hillsides, especially where the subsoil is underlaid by clay. Large landslips are generally confined to young mountain ranges, such as the Alps, where anticlines are common. For example, a memorable landslip took place at Rossberg, in Switzerland, in September, 1806, after a season of heavy rains. A portion of the mountain-side, measuring 2½ miles long, 350 yards wide, and 35 yards thick, suddenly fell into the valley of Goldau, burying four villages and about 500 of their inhabitants.

The action of the sea as a geological agent is twofold: it erodes the coast-line, and it transports and collects sediment.

1. **Marine Erosion.**—The chief causes of the gradual wasting away of coasts may be summed up as follows:—

(*a*) *The energy of the advancing waves and breakers.* The average force with which Atlantic rollers beat upon our west coasts in summer is about 600 lbs. per square foot, in winter about 2000 lbs. per square foot, and during a storm 3 or 4 tons per square foot. Such waves, throwing themselves against the cliffs and hurling their spray far up them, must by their friction and dynamic force wear away the rocks and wrench off loose masses.

(*b*) *The bombardment of the coast by the loose pieces of rock, shingle, and sand hurled against it by the waves.* Just as rivers owe their eroding power mainly to the sediment they move along, so the destructive action of the sea is chiefly due to the detritus set in motion by the waves and breakers. In storms masses of rock weighing from 3 to 5 tons have been tossed about like pebbles, and Stevenson, the lighthouse engineer, mentions the moving of a block weighing 50 tons by the waves at Barrahead, in the Hebrides.

(*c*) *The hydraulic pressure exerted by the water forced into cracks by the impact of the waves helps to disrupt the rocks.* Also, when a wave strikes against a cliff it powerfully compresses the air in all the joints and crevices of the rock, thus sending a sudden blow through its whole mass, and when the wave subsides the air as suddenly expands and hurls out loosened fragments.

(*d*) *Chemical solution.* Doubtless the sea dissolves out certain of the constituents of the rocks, and thus leads to the disintegration of the latter; but this is not nearly so important as the three forms of mechanical action just mentioned.

Marine erosion takes place mainly between the tide-marks and as much higher as waves and breakers can reach. It is chiefly an undermining action, causing the projecting parts to fall by their own weight, and therefore the coast-line to gradually recede, the work being greatly assisted above the

water-level by the ordinary atmospheric agencies. The action of the sea has been aptly compared to that of a great horizontal saw cutting into the margin of the land, the vertical distance between high and low water mark representing, as it were, the width of the saw-cut.

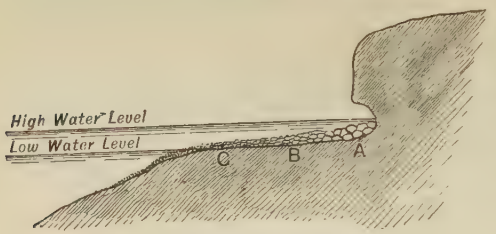


Fig. 126.—Formation of a beach.

The general erosive action of the waves resulting in the formation of beaches and cliffs is illustrated in Fig. 126. The rocks get undermined, and portions fall in the manner already described. These are coarse and angular, as at A, but by the rolling to and fro and rubbing against each other they are rounded and broken into finer fragments, as at B, and still finer fragments forming sand and mud are spread out farther from the land, as at C. A typical sea-beach has been excellently described as follows[1] :—

"The name *beach* is restricted to the strip of land covered and laid bare by the tides. On a typical beach large stones are usually found heaped up near high-water mark ; smaller pebbles, rounded by the sea, form a steeply sloping bank at a lower elevation, and are rattled to and fro, ground against each other, reduced in size to fine shingle, and raked nearer the sea by every tide. Next, there is a wide stretch of sand, which usually consists of quartz grains resulting from the breaking down of pebbles, the quartz being the densest and hardest ingredient of the rocks. Nearest the sea, and often only uncovered at the lowest spring ebbs, there are banks of mud formed of the softest ingredients of the rocks, which are ground to the finest powder and carried to the greatest distance."

The form of the cliffs will depend upon the nature of the rocks composing them. If they be homogeneous in composition, like chalk or sandstone, they will tend to form a regular line of cliffs ; but if they be of variable composition, they will yield unequally to the action of the sea, and form every variety of bays and promontories, caves, gullies, and isolated rocks variously called stacks, needles, or outliers. Bays are caused by soft or exposed rocks being worn away more quickly than the hard or protected rocks of which headlands are composed. For example, at Flamborough and Spurn Heads the ends of

[1] Dr. H. R. Mill in *The Realm of Nature*, p. 199 (John Murray).

ranges of hills project into the sea. Islets and stacks may owe their preservation to their hardness as compared with the

FIG. 127.—The Stacks of Duncansby. Marine erosion on a rocky coast. (From Bird's *Advanced Geology*.)

material that once surrounded them, or sometimes to the fewness or absence of joints in the rock.

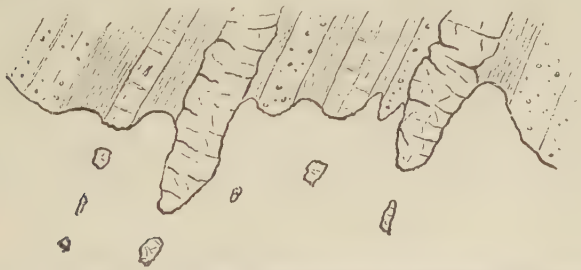


FIG. 128.—Ground-plan of a sea-coast showing the irregular outline due to alternations of harder and softer rocks. (From J. Geikie's *Outlines of Geology*.)

No careful observations of the rate of destruction of the land by the sea have yet been made. Sir A. Geikie roughly estimates it as 10 feet in a century. Some parts of our coasts composed of clay or soft chalk are being washed away at the rate of from 1 to 3 yards yearly, and on the Yorkshire coast the sites of former towns and villages, such as Auburn, Ravenspur, and Hyde, are now submerged. The same fate has befallen the old city of Dunwich, in Suffolk.

2. **Transport and Deposition of Sediments.**—The *débris* brought down by rivers, or derived from the coast by the denuding action of the sea, is carried by currents and spread over the ocean floor, the coarser materials falling near the land, and the finer ones farther out, thus forming the terrigenous deposits described in Chapter XII. From the explorations of the *Challenger* and other surveying ships, we learn that the continental detritus is never carried beyond 300 miles from land.

Formation of Stratified Rocks.—The sedimentary rocks forming such a large part of the earth's surface have been deposited in the shallow water round continents or in lakes, and have afterwards been upraised to their present position. Unconformabilities (see p. 224) show that such elevations above sea-level and depressions below it have taken place repeatedly.[1]

Sedimentary rocks invariably show a bedded arrangement; that is to say, occur in layers. If the layers are thin—sometimes in shale and other rocks they are as thin as paper—they are called *lamina*, and this structure arises from the accumulation having taken place in an intermittent manner, as by being deposited in a sheltered estuary by successive tides, or by the material being mainly brought down during periods of flood, as in the case of rivers in regions with rainy seasons alternating with seasons of drought. *Strata* are layers of rock varying from less than an inch up to several feet in thickness, and they show that the material had gone on accumulating for a lengthened period, and then ceased, perhaps owing to some change in the river-basin. After an interval the accumulation began again and formed another layer, and so on.

The hardening of the incoherent mass is brought about partly by pressure, and partly by the particles being cemented together by materials in solution in the water percolating through the deposit.

QUESTIONS.

1. What is meant by denudation, and what by weathering? How would you prove to a class that denudation is taking place at the present time?

[1] Amongst the sedimentary deposits on the earth's surface we find no rocks corresponding to the deep-sea deposits, hence we infer that the changes from sea into land and land into sea have been confined to the margins of the oceans, that the depths of the oceans probably have never been dry land, and that the continents have never formed part of the depths of the ocean.

2. What is meant by sub-aërial denudation, and what are the chief agents engaged in it?

3. Describe the chemical and mechanical agencies by which rocks are disintegrated.

4. Describe the action of rain in producing sub-aërial denudation.

5. Explain the action of frost in breaking up rock-masses. Where does this kind of action go on most rapidly?

6. Give a brief account of the work of rivers as geological agents.

7. Compare the action of rain and rivers in producing the features of the earth's surface.

8. State what rock-constituents are carried by rivers to the sea in suspension and solution respectively; and describe what becomes of those materials when they reach the sea.

9. Explain the methods by which the quantity of material carried down by rivers, in suspension and solution respectively, can be determined. How may this be made to gauge the rate of sub-aërial denudation within the river-basin?

10. The River Rhone enters the Lake of Geneva as a muddy stream, and leaves it as a perfectly clear one. State the source whence the sediment carried by the river is derived, and what becomes of it. Explain the changes which are being produced in the physical features of the country by the removal and redeposition of the material carried by the river.

11. Give a brief account of the work of glaciers as geological agents.

12. (*a*) Describe the manner in which rivers convey the materials of the land from higher to lower levels. (*b*) Describe the manner in which glaciers convey the materials of the land from higher to lower levels. (*c*) What do you know concerning the comparative rates of movement of rivers and glaciers? (*d*) What becomes of the materials conveyed by rivers and glaciers respectively?

13. In what respects do rivers and glaciers resemble one another? State how they differ from one another in their mode of transport of materials from mountains to the sea.

14. Give instances of the action of rain, rivers, and glaciers in changing the form of the earth's crust.

15. What evidences have we that there was a glacial period in this country, and therefore that our climate has undergone great changes?

16. What is meant by "glacial striation," and how is it produced?

17. Describe the phenomena called *roches moutonnées*, and explain how they are formed.

18. What is meant by soil, and how is it formed?

19. Tell briefly what you know about the geological action of springs.

20. What are landslips, and how are they caused?

21. Give an account of the work of the sea in wearing away coasts, and in the transport and deposition of sediments.

22. Describe the mode of formation of stratified rocks.

CHAPTER XVI.

POSITIONS AND DISTANCES OF HEAVENLY BODIES.

Determination of the Directions of Heavenly Bodies.—In order to make a scientific study of the celestial objects, it is essential that we should have some method of definitely specifying their positions in the heavens; and just as we determine the position of a place on the earth's surface by two angular measurements at right angles to each other, namely, latitude and longitude, so we fix the direction of any object in the sky by two angular measurements at right angles to each other. Three different systems of measurements are in use—

(1) The Horizon System, viz. altitude and azimuth, which are measured relatively to the astronomical horizon.

(2) The Equinoctial System, viz. declination and right ascension, which are measured relatively to the equinoctial or celestial equator.

(3) The Ecliptic System, viz. celestial latitude and longitude, which are measured relatively to the ecliptic.

The Horizon System.—Altitude and azimuth were explained in the elementary book (pp. 256–258), and we shall merely repeat the definitions here—

The altitude of a heavenly body is its angular distance above the horizon, measured along the vertical circle passing through the body.

The azimuth of a heavenly body is the arc of the horizon measured from the south point of the horizon eastwards to the vertical circle passing through the body. Azimuth may have any value from 0° up to 360°.

The Equinoctial System.—Altitude and azimuth only give the direction of a star from a particular place at a particular time, hence declination and right ascension are much more convenient, being definite quantities for the star and independent of the place and time of observation.

The points where the earth's axis of rotation prolonged

indefinitely would meet the celestial sphere are called the *celestial poles.* The great circle passing round the celestial sphere midway between the two poles is called the *equinoctial*, or the *celestial equator* since its plane is the same as that of the earth's equator.

Great circles that pass through both celestial poles cut the equinoctial at right angles. They correspond to meridians on the earth, and are called *hour-circles.*

The declination of a celestial body is its angular distance from the equator measured along the hour-circle passing through the body. If the star is north of the equator, it is said to be in north or positive (+) *declination; and if south, then in south or negative* (−) *declination.* Declination therefore ranges from 0° to + 90° or − 90°. Its complement is called *polar distance*, being the angular distance of the star from the celestial pole.

The hour-circle of a star coincides with the meridian of any place once a day. At any other time they intersect at a certain angle at the pole, because the meridian of the place is carried eastwards 15° per hour by the rotation of the earth. *The hour-angle, therefore, of a star is the angle at the pole between the hour-circle of the star and the meridian of the place.* It enables us to tell the time that will elapse before the star reaches the meridian, or that has passed since it crossed it.

The student will have already learned that *the ecliptic is the circle in the heavens which the sun seems to describe in a year*, and that its inclination to the equinoctial is $23\frac{1}{2}°$. The two points of intersection of these circles (ecliptic and equinoctial) are called equinoctial points, because the sun in its apparent motion along the ecliptic is at one of them at the spring equinox, and at the opposite one at the autumn equinox. The former is known as the *vernal equinox*, or *First Point of Aries* (because, when this name was first applied, the sun entered the constellation of Aries at spring), and the latter as the *autumnal equinox*, or *First Point of Libra.*

The right ascension (*R.A.*) *of a heavenly body is the arc of the equinoctial measured from the First Point of Aries eastwards to the hour-circle of the body.* It may therefore be as great as 360°. As a matter of convenience, *right ascension is generally expressed in hours, minutes, and seconds;* and as 24 hours comprise the entire round of the sky, and 360° do the same, one may easily be substituted for the other.

The Ecliptic System.

The celestial latitude of a star is its angular distance north or

south of the ecliptic, measured on the great circle passing through the star and the pole of the ecliptic.

The celestial longitude of a star is the arc of the ecliptic, measured from the First Point of Aries eastwards to the great circle passing through the star and the pole of the ecliptic.

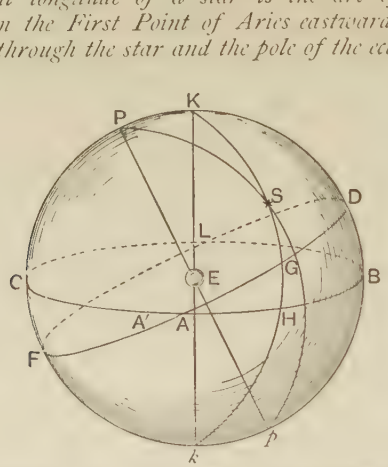


FIG. 129.—To illustrate the equinoctial and ecliptic systems of defining the direction of a star. The shaded sphere represents the starry heavens round the earth E.

ABLC, ecliptic.
ADLF, equinoctial.
K, pole of ecliptic.
P, celestial pole, or pole of equinoctial.
A, First Point of Aries.
L, First Point of Libra.
S, position of a star.
AG, right ascension of star.
GS, declination of star.
AH, longitude of star.
HS, latitude of star.
Angle BAD, obliquity of ecliptic.

Of the three systems of indicating the directions of heavenly bodies, the second is the one nearly always employed, and we shall therefore briefly describe the instrument used for measuring right ascension and declination.

The Meridian Circle or Transit Circle.

1. There is a telescope, T (Fig. 130), fixed at right angles to a rigid axis, WE, which is hollow in the interior for lightness. WE lies exactly west and east, and is perfectly horizontal.

2. The cylindrical ends of WE rotate freely in two forks called Y's from their shape. These Y's rest on piers, P, of solid stone built on the firmest possible foundations.

3. A vertical graduated circle, GH, is attached near one end of the axis WE (sometimes there is one near each end), so that the axis, telescope, and circle rotate as one piece. The readings are made to tenths of a second by means of a fixed compound microscope, I, called the index or pointer.

4. Beside the instrument there stands an astronomical clock keeping sidereal time. It reads 0 h. 0 m. 0 s. when the First Point of Aries crosses the meridian, and the hours are reckoned up to 24, when the First Point of Aries again crosses the meridian and a new astronomical day begins.

It should, perhaps, be remarked that when the instrument is not provided with a vertical graduated circle, GH, it is called a *transit instrument*, and can then only be used for right ascension and time measurements.

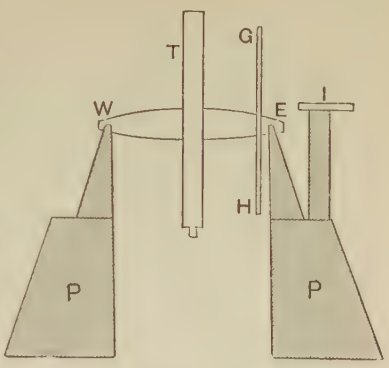


FIG. 130.—Diagram of the essential parts of a transit circle.

Uses of the Transit Circle.

1. *To determine Right Ascension.*—From the way in which the telescope is fixed, we see that it can only rotate in the plane of the meridian, and therefore can only view heavenly bodies when they transit or cross the meridian. But as the field of view covers a considerable area, it would be difficult to say when a star is exactly in the centre of the field; hence within the telescope tube, at the common focus of the object-glass and eye-piece, there is a system of stretched spider-threads (Fig. 131), two of which are fixed horizontally and nearly in contact, and an odd number (five or seven) vertically and at equal distances apart. What an observer has to do in order to measure the R.A. of a star is to incline the telescope at such an angle

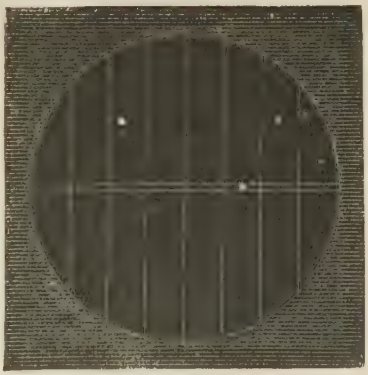


FIG. 131.—The field of view of a transit circle, showing the reticle or system of spider lines, the central vertical one of which lies in the meridian.

that the star is seen to travel along the space between the two horizontal threads, and then to record, by means of the astronomical clock, the time when the star crosses each of the vertical threads; then, by taking the average of these five or seven observations, the time of the star's meridian passage is obtained with greater accuracy than if the transit of the central wire only had been observed. Suppose the average is 21 h. 17 m. 20 s., this is the star's R.A.; and if we wish to transform it into angular measure, then, since 1 h. = 15°, therefore R.A. = $21\frac{1}{4}\frac{3}{5} \times 15 = 319° 20'$.

2. *To determine Declination.*—If the vertical graduated circle is so fixed that it indicates 90° when the telescope is pointed to the celestial pole (or 0° when pointed to the equinoctial), then, when a star is crossing the meridian, the reading on the vertical circle is the star's distance from the equinoctial, that is, its declination.

The above are the two chief uses of the transit circle, but it can also be employed for the following purposes :—

3. *To check a Sidereal Clock.*—The Nautical Almanac gives the R.A. of prominent heavenly bodies. Suppose that according to the Almanac the R.A. of α Tauri is 4 h. 29 m. 32 s., then if, on comparing this with the time indicated by the sidereal clock when the star is transitting, there is a difference, it will be the amount of the clock's error.

4. *To check a Mean-time Clock.*—Select a star whose R.A. is given in the Nautical Almanac, and change this sidereal time into mean solar time by tables prepared for the purpose. Then by comparing this with the time shown on an ordinary clock at the moment that the star is observed to transit, we can tell how much the clock is wrong.

5. *To find the latitude of the place* is one of the first uses made of the instrument after it is fixed. For the method, see *Elementary Physiography*, p. 272.

6. *To measure the Meridian Altitude of a Star.*—The method is simple, but is beyond the province of this book.

Precautions necessary in fitting up a transit circle.

1. *The line of collimation or optical axis* (*i.e.* the imaginary line joining the centre of the object glass to the centre of the eye-piece) *must be at right angles to the west and east axis* WE. The test for this is to observe a distant object, such as a building, and note what part of it falls on the intersection of the central spider threads; then the axis WE is reversed in its supports, so that the end that was to the east is now to the west, and if the same part of the object is still at the intersection of the central threads the collimation is correct, and if not the threads are moved until the error is corrected.

2. *The axis WE must be perfectly west and east*, otherwise the instrument will not move truly in the meridian. To test this, observe the upper and lower transits of a circumpolar star; if the interval between them is exactly twelve sidereal hours, then the instrument is moving in the plane of the meridian.

3. *The axis WE must be perfectly horizontal.* This is tested by a spirit-level suspended from WE, and of sufficient length to stretch from one bearing to the other, and therefore called a striding level.

In many instruments the Y's can be adjusted by screws to correct errors in (2) or (3).

4. *The vertical circle must read* 90° *when the telescope is directed to the celestial pole.*

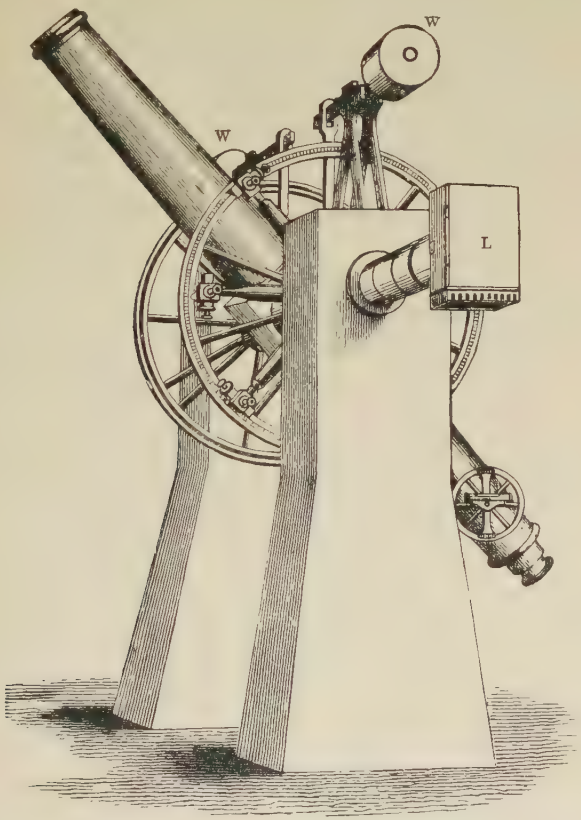


FIG. 132.—Meridian or transit circle. W, W are counterpoises to prevent the bearings from yielding under the pressure of the instrument. L is a lamp for illuminating the spider threads at night. (From Brinkley's *Astronomy*.)

Explanation of Parallax.—Declination and right ascension only tell us in what direction to look for a heavenly

body; they do not fix its position. In order that this may be the case we must know what the body's distance is in that direction: that is to say, we must know its distance from the earth. The problem of determining the distance of a heavenly body resolves itself, as we shall show, into finding its parallax. We must first, however, explain what this word means.

If the direction of a prominent object in a landscape, say a neighbouring church tower, were observed it might be found to be north-east, suppose; but if we changed our standpoint the direction of the tower would be different, perhaps north. This change of direction is called parallax, which we might therefore define, *in the most general sense*, as the change in direction of a body as viewed from two different standpoints. It is similar with heavenly bodies viewed from different places on the earth. For example, if S (Fig. 133) were a celestial body, such as the moon or a planet, then an observer at A would see it in the direction AS, whereas an observer at B would see it in the direction BS. To prevent confusion of this kind, a standard position is taken, namely, the centre of the earth, and the true direction of a heavenly body is held to be that in which it would be seen if it could be viewed from the centre of the earth, and reducing any direction to this standard is called *making the correction for parallax*. Thus the parallax of a heavenly body at a place is the difference in the direction of the body as viewed from that place and from the centre of the earth. In Fig. 133, the angle ASC is the parallax of S at A, and the angle BSC is its parallax at B. As the standard position is the centre of the earth, this is called the geocentric or diurnal parallax. Hence, *at any place the geocentric or diurnal parallax of a heavenly body is the angle which the radius of the earth passing through the place subtends at the heavenly body.*

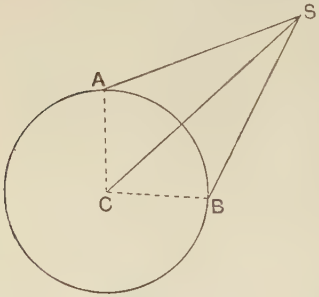


FIG. 133.—To illustrate geocentric parallax.

When a heavenly body is in the zenith its parallax is zero, for in Fig. 134 the radius CO (O being the position of the observer) subtends no angle at Z. As the body descends from the zenith its parallax increases, and is a maximum when the body

is on the horizon as at S, and this is called the *horizontal parallax.* But since the earth is not a perfect sphere, its radius is not of the same length in all directions, hence to avoid having to specify always which radius is in question, the equatorial radius of the earth is adopted as the standard, and therefore *the geocentric equatorial horizontal parallax is the angle subtended at the heavenly body by an equatorial radius of the earth when the body is on the horizon.* If the kind of parallax is not specified, this is the one that is meant.

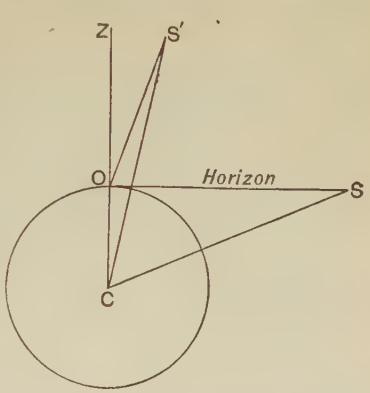


FIG. 134.—The geocentric parallax of a heavenly body is greatest when it is on the horizon, and is *nil* when it is in the zenith.

The equatorial horizontal parallax of the moon averages 57′ 2″, that of the nearest planet 40″, and that of the sun 8″·8, whence it is evident that *the greater the distance of a body, the less is its parallax.*

The Distance of a Body calculated from its Parallax.—The whole circumference of a circle ($2\pi r$, where π is the familiar 3·14159, or $3\frac{1}{7}$) subtends at the centre of the circle an angle of 360°, or 1,296,000″, therefore an arc equal to the radius subtends at the centre an angle of $\frac{1296000''}{2 \times 3\frac{1}{7}}$, or 206265″ nearly. By utilizing this fact, we can calculate the distance of a celestial body in miles when its parallax is known. Let p'' be the parallax of the body, and R the earth's radius; then the question is, If the earth's radius viewed at a distance R subtends an angle of 206265″, at what distance would it subtend an angle of p″? Call this distance D, and remember that it is a case of inverse proportion (for the greater the distance the less the parallax); then we have the following proportion:—

$$p'' : 206265'' :: R : D$$
$$\therefore D = \frac{206265R}{p''}$$

or, expressed in words, *the distance of a heavenly body is equal to* 206265 *times the radius of the earth, divided by the geocentric parallax of the body expressed in seconds of arc.* For example, the parallax of the moon is found to be 57′ 2″ or 3422″;

$$\therefore \text{distance of moon} = \frac{206265 \times 3960 \text{ miles}}{3422}$$
$$= 240{,}000 \text{ miles, approximately.}$$

Again, the parallax of the sun will be shown to be 8″·8 ;

$$\therefore \text{distance of sun} = \frac{206265 \times 3960 \text{ miles}}{8{\cdot}8}$$

$$= 92{,}800{,}000 \text{ miles, approximately.}$$

The above formula is an exceedingly important one, and may be expressed in the more general form—

$$\text{distance of object} = \frac{206265 \times \text{base-line (in miles)}}{\text{parallax (in seconds of arc)}}.$$

Distance of the Moon.—The movement of the moon makes it difficult to measure its parallax, and to render the effect of this very small, the position of the moon is observed at, or very nearly at, the same instant from two observatories far removed from each other and on, or very nearly on, the same meridian. Greenwich and Cape Town have been found most suitable, and indeed it was primarily for the purpose of finding the moon's distance that the Royal Observatory at Cape Town was founded early in the nineteenth century. Let G and C in Fig. 135 represent Greenwich and Cape Town re-

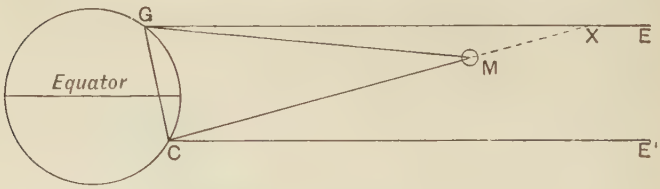


Fig. 135.—Measurement of the moon's distance.

spectively, and let GE and CE′ be drawn parallel to the equator. Then the angles MGE and MCE′ are the declination of the moon at Greenwich and Cape Town respectively. These are measured, and in this way the angle GMC is known, for it is equal to the sum of the angles MGX and MXG (when the moon is between GE and CE′, as in the diagram), that is, to the sum of the angles MGE and MCE′ (for MXG is equal to MCE′, since the lines GE and CE′ are parallel). But the angle GMC is the parallax of the moon due to the difference in the positions of observation at G and C.

Hence the formula—

$$D = \frac{206265 \times \text{base line}}{\text{parallax in seconds}}$$

becomes in this case—

$$D = \frac{206265 \times \text{length of GC}}{\text{angle GMC reduced to seconds}}.$$

But the length of the straight line GC is accurately known from the position of the places and the size of the earth, and we have shown that the angle GMC is known, and thus the distance D of the moon is found. The average distance of the moon is about 238,840 miles, or 60·27 times the equatorial radius of the earth.

. Two stations with suitable observatories cannot be found on exactly the same meridian, but the above method is used with a correction for the change of declination of the moon in the interval between its transit over the two meridians.

Distance of the Sun.—The parallax of the sun is so small that the method employed for the moon fails when applied to the sun, for an inaccuracy in the measurement of parallax that would cause an error of 100 miles in the moon's distance would vitiate the result in the case of the sun to the extent of 16 million miles. Yet it is of the utmost importance to science to ascertain the sun's distance with the greatest possible accuracy, for it is the fundamental unit of celestial measurement, and if it is wrong all the other distances in the solar system are wrong too. Hence many different methods have been employed for its measurement, that they may act as a check upon each other.

I. *By Observations of the Transit of Venus.*—Since the orbit of Venus is within the earth's orbit, she occasionally comes exactly between us and the sun, and is seen like a small black dot moving across the shining disc. This is called a transit of Venus, and the following is an outline of *Delisle's method* of utilizing the phenomenon to find the solar parallax.

The observation stations, W, E (Fig. 136), are taken at opposite ends of a diameter of the earth near the equator, and in the same plane as the orbit of Venus. Then the observer at W notes in Greenwich time the moment of internal contact (*i.e.* the moment when the planet has completely entered the sun's disc, as shown at A in the figure), Venus being then at V_1. Some time afterwards the observer at E sees the same phenomenon, and notes its exact Greenwich time, the planet having in the interval moved to V_2. But Venus goes right round the

sun and catches up the earth again in 584 days; that is to say, she gains 360° on the earth in 584 days, and from this we can tell what angle she gains in the observed time taken to pass

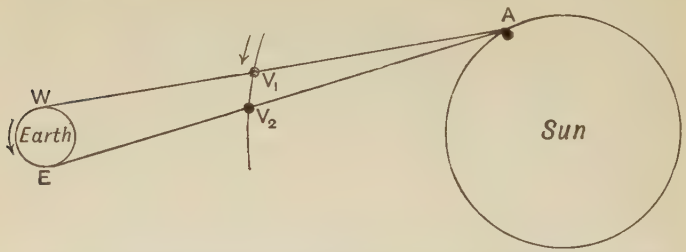


FIG. 136.—Delisle's method of determining the sun's distance by an observation of the transit of Venus.

from V_1 to V_2. This is the angle at A, which is the angle subtended at the sun by the equatorial diameter WE of the earth, and hence half this angle will be the equatorial parallax of the sun.

Owing to various defects, chief among which is the difficulty of deciding the *exact* moment of internal contact (for three atmospheres—the solar, terrestrial, and Cytherean—all help to cause blurring), the transit of Venus is not now considered by any means the best method of determining the distance of the sun.

II. *By Observations of the Parallax of a Superior Planet when in opposition.*[1]—Mars is one of the most suitable for this purpose, and its most favourable oppositions are those that occur when Mars is in perihelion and the earth in aphelion, for

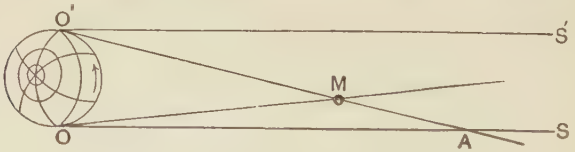


FIG. 137.—Determination of the parallax of Mars and the distance of the sun.

then Mars is at its minimum distance from the earth. The observer takes his position at O (Fig. 137) on or near the equator (the Island of Ascension has been used for the purpose), and when Mars is rising it is seen in the direction OM, while a

[1] For the astronomical meaning of the word "opposition," see p. 315.

neighbouring star is seen in the direction OS, and the observer carefully measures the angular distance of Mars from the star. This is the angle MOS. Twelve hours afterwards the rotation of the earth will have carried the observer to O′, and Mars will be setting, and it will be seen in the direction O′M, whereas the star, because of its great distance, will be seen in the same direction as before, namely, O′S′. The observer again measures the angular distance of Mars from the star. This is MO′S′. Hence the angle OMO′ is known, for in the position represented in the figure it is equal to the sum of the angles MOA and MAO—that is, to the sum of the angles MOS and MO′S′ (for the angle MAO is equal to the angle MO′S′, since the lines OS and O′S′ are parallel). But the angle OMO′ is the angle subtended at Mars by the equatorial diameter OO′ of the earth, and hence half of this angle is the equatorial horizontal parallax of Mars, and, having obtained this, the distance of Mars is found from the relation—

$$D = \frac{206265 \times 3960 \text{ miles}}{p''} = \text{about } 33{,}000{,}000 \text{ miles.}$$

From this we get the parallax and distance of the sun, for by Kepler's third law we know that the distance of the earth from the sun is almost three times that of the earth from Mars.

This is now considered a more accurate and less cumbersome method than No. I., because one observing-station is sufficient, the rotation of the earth supplying the base-line, and also because the method can be applied to about a dozen of the brightest of the minor planets (p. 329), and very short times elapse before one or other of these is in a suitable opposition for the necessary observations.

III. *From the eclipses of Jupiter's satellites and the known velocity of light.*—The time taken by light to traverse the distance between the earth and the sun is called "the equation of light," and we have explained at p. 55, Fig. 27, how Roemer, by observations of the eclipses of Jupiter's satellites, determined this to be 498 seconds. But we have already shown that light travels 186,330 miles per second, hence the distance between the earth and sun must be 186,330 miles × 498, or 92,792,340 miles.

IV. *From the Constant of Aberration and the Known Velocity of Light.*—On p. 56 we explained how, if we knew the velocity of the earth in its orbit, we could, from the constant of aberration, determine the velocity of light. Conversely, if

the velocity of light be found by one of the other methods, then we can use this one to determine the velocity of the earth in its orbit, and therefore the distance of the sun. We need not here repeat the explanation on p. 58 and Fig. 30, that—

$$\frac{\text{velocity of earth in its orbit per second}}{\text{velocity of light per second}} = \text{tangent } 20''{\cdot}5$$

therefore—

$$\frac{\text{velocity of earth in its orbit per second}}{186{,}330 \text{ miles}} = \frac{1}{10000}$$

therefore—

velocity of earth in its orbit per second = 18·633 miles.

Multiplying this by the number of seconds in a year, we find the circumference of the earth's orbit to be 18·633 miles × 60 × 60 × 24 × $365\frac{1}{4}$. But we get the length of the circumference of a circle by multiplying its radius by twice $3\frac{1}{7}$, and the earth's orbit is very nearly a circle having the line joining the earth and sun for radius; hence—

$$2 \times 3\tfrac{1}{7} \times \text{distance from earth to sun} = 18{\cdot}633 \text{ miles} \times 60 \times 60 \times 24 \times 365\tfrac{1}{4}$$

$$\text{therefore distance from earth to sun} = \frac{18{\cdot}633 \text{ miles} \times 60 \times 60 \times 24 \times 365\frac{1}{4}}{2 \times 3\frac{1}{7}}$$

= nearly 93,000,000 miles.

After discussing the values of the solar parallax given by all the different methods, Professor Harkness, an authority on the subject, believes that its most probable value is 8″·80905, and, converting this into miles by the equation—

$$D = \frac{206265 \times \text{radius of earth in miles}}{\text{parallax in seconds}}$$

we find the distance of the sun to be 92,796,950 miles, with a probable error of not more than 60,000 miles either way.

Definition of Aberration of Light, and Method of determining the Constant of Aberration.—From the explanation given on pp. 56–58, we see that *the aberration of light means the apparent displacement of a star owing to the combination of the velocity of light with the velocity of the earth in its orbit*, for if either DE or FE, in Fig. 30, were to alter, the angle FDE would be affected.

By measuring the right ascension and declination of any star day by day throughout the year, and marking the corresponding positions on a celestial chart or globe, we would thereby trace the aberration orbit of the star. In every case in which this is done it is found that the orbit is parallel to the ecliptic, and has a major axis always 41″ in length. That is to say (since the actual position of the star is at the centre of the ellipse), the star always seems 20″·5 in advance of its true place, and hence this is called the *constant of aberration.* 20″·5 is its mean value, for it varies slightly because of the variable rate of the earth in its orbit, being $20\frac{5}{6}$″ when the earth is at perihelion, and $20\frac{1}{6}$″ when at aphelion.

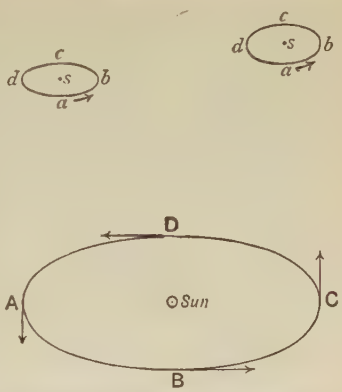


FIG. 138—ABCD is a perspective view of the earth's orbit. When the earth is at the point A, and moving for the moment in the direction indicated by the arrow, the star *s* will seem displaced in the same direction, and will therefore appear to be at *a*. Similarly, when the earth is at B, C, and D, the star will seem to be at *b*, *c*, and *d* respectively. Hence, owing to aberration, each star seems to describe an ellipse round its true position in the same direction as the earth travels in its orbit.

Distances of Other Planets from the Sun.—The determination of the earth's distance from the sun leads at once to those of the other planets, for Kepler's third law [1] states the relative distances to be such "that the squares of the periodic times of planets are proportional to the cubes of their mean distances from the sun." The time that each planet takes to go round the sun can be determined by observation, and the results are given in the fourth column of the table on p. 311. Suppose, for example, a new planet were discovered with a period of 8 years, then, by the above law—

$$1^2 : 8^2 :: 93^3 : \text{cube of distance of planet from sun}$$

$$\left.\begin{array}{l}\text{therefore cube of distance}\\ \text{of planet from sun}\end{array}\right\} = 8^2 \times 93^3$$

$$= 64 \times 93^3$$

$$= 4^3 \times 93^3$$

therefore distance of planet from sun $= 4 \times 93$, or 372 million miles.

Then, having obtained the distances of planets from the sun, their distances from the earth at once follow. We

[1] *Elementary Physiography*, p. 276.

described, however, an independent method of determining the distances of Mars and the minor planets from the earth when they are in opposition.

Distances of Stars.—In measuring the distances of stars the radius of the earth is far too small a base-line, for so distant are the stars that the earth's radius subtends no appreciable angle at them, or, to express it otherwise, if a line 3960 miles long on the earth were viewed from a star, it would seem a mere point. The longest base-line available to us is that joining the centre of the sun with the centre of the earth, and the parallax obtained from it is therefore called the heliocentric parallax, and sometimes the annual parallax since it is connected with the yearly motion of the earth. Hence *the annual or heliocentric parallax of a star is the angle which the radius of the earth's orbit subtends at the star.* When this has been determined, then we get the distance of the star from the relation—

$$D = \frac{206265 \times \text{base-line in miles}}{\text{parallax in seconds of arc}}$$

$$\text{i.e. distance of star} = \frac{206265 \times 93{,}000{,}000 \text{ miles}}{\text{heliocentric parallax of star expressed in secs.}}$$

Modern Methods of determining the Parallax of Stars:—

1. *Bessel's differential method.* We found the moon's distance by measuring its displacement among the neighbouring stars as seen from two distant observatories, and by a similar method we can find the distance of a few of the nearer stars by measuring their displacement among the "fixed" stars when viewed from different parts of the earth's orbit. It is evident from Fig. 139 that as the earth moves round the sun, a nearer star seems projected upon different parts of the sky, and in the course of a year seems to describe in this way a small ellipse, called the star's parallactic orbit (since it is due to parallax), the size of which, however, depends upon the distance of the star. The vast majority of stars are so distant that no annual parallax can be determined, and their parallactic orbit is a mere point.

The method of determining stellar parallax introduced by Bessel, an eminent German astronomer, is to measure night by night throughout the year, by means of telescopes with micrometer eye-pieces, the change in the position of the star, whose parallax we are seeking, among the faint stars in the same field of view. This change of direction is not the absolute parallax of the star, but is *the difference* between its parallax and that of the faint star (hence the name *differential method*); but because of the great distance of the latter its parallax will be almost nil, and having measured the parallax of the bright star relatively to several faint stars in the same field, we can deduce the actual parallax of that star.

2. *The photographic method* is exactly the same in principle as the last, but instead of making the above measurements by means of a micrometer or other instrument, the region of the sky in which the star lies is photographed at different times, and therefore from different standpoints, and

then by careful measurements of the images on the plates, we can determine the change of position of the bright star among the faint ones near it. This method is (at least) as accurate as the preceding one, and is much less laborious, for Bessel took almost three years to determine the distance of a star, whereas about four photographs taken at different times each night for a month provide sufficient data by the newer method.

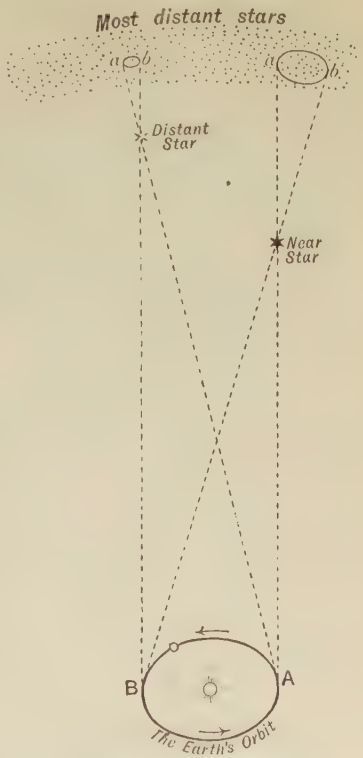


FIG. 139.—Stellar parallactic ellipses due to the earth's revolution round the sun. The nearer a star is, the larger is its apparent parallactic ellipse. Half the angle shown at a star is its annual parallax.

Only a few of the stars are near enough to us to show any appreciable parallax, and the parallaxes of only about fifty stars have yet been reliably determined, and a few of these are given in the following table. So far as yet discovered, our nearest stellar neighbour is α Centauri, 30° from the south celestial pole, and therefore invisible in this country. To say that its distance from the solar system is 25 millions of millions of miles conveys no meaning to the human mind, and yet stars have been found by measurement to be a hundred times more remote than this. Even the astronomical unit (93,000,000 miles) used for expressing distances in the solar system is inconveniently small for expressing the distances of stars, and hence a unit 63,000 times larger has been adopted by astronomers as the unit of stellar distance. It is the distance that light travels in a year, and therefore the unit is termed the *light-year*. We give a few of the most recent results for reference—

STELLAR DISTANCES AND PARALLAXES.

Name of star.	Magnitude.	Parallax.	Distance in light-years.	Proper motion.
		"		"
α Centauri	−0·1	0·75	$4\frac{1}{3}$	3·67
61 Cygni	5·1	0·45	$7\frac{1}{3}$	5·16
Sirius	−1·4	0·38	$8\frac{1}{2}$	1·31
Groombridge 1830 . . .	6·5	0·13	25	7·65
Vega (α Lyræ)	0·2	0·12	27	0·36
Aldebaran	1·0	0·10	32	0·19
Polaris (Pole Star) . . .	2·1	0·07	47	0·05
Arcturus	0·2	0·02	160	2·00

Determination of the Diameter in Miles of a Heavenly Body whose Distance and Angular Diameter are known.—Suppose AB (Fig. 140) to be the heavenly body, C its centre, and E the earth. Then the distance CE is known, and so is the length of CA in angular measure—that is to say, the magnitude of the angle AEC. Then

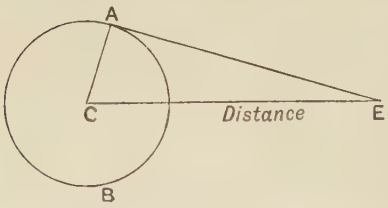


FIG. 140.—Method of determining the diameter in miles of the sun, planets, or satellites whose distances and angular diameters are known.

the relation—

$$D = \frac{206265 \times R}{f''}$$

becomes—

$$CE = \frac{206265 \times AC}{\text{angle AEC in seconds}}$$

$$\therefore AC = \frac{CE \times \text{angle AEC in seconds}}{206265}$$

$$\text{that is, radius in miles} = \frac{\text{distance} \times \text{angular semi-diameter in secs.}}{206265}$$

$$\text{therefore diameter in miles} = \frac{\text{distance} \times \text{angular diameter in seconds}}{206265}$$

For example, taking the angular diameter of the sun as 32′, or 1920″, then—

$$\text{diameter of sun} = \frac{92{,}800{,}000 \times 1920}{206{,}265}$$
$$= \text{about } 866{,}000 \text{ miles.}$$

Similarly, the angular diameter of the moon is 31′ 7″, or 1867″, and its distance is 238,840 miles;

$$\text{therefore diameter of moon} = \frac{238{,}840 \times 1867}{206{,}265}$$
$$= \text{about } 2163 \text{ miles.}$$

Once more, on April 14, 1895, the angular diameter of Saturn was 17″·9, and its distance 9·54 times that of the earth from the sun—

$$\text{therefore diameter of Saturn} = \frac{9{\cdot}54 \times 92{,}800{,}000 \times 17{\cdot}9}{206{,}265}$$
$$= \text{about } 76{,}500 \text{ miles.}$$

Instruments used in Astronomical Observatories.—Perhaps this is the best place in which to mention the chief instruments in an astronomical observatory:

1. *Telescopes* for increasing our power of vision. They are of two kinds—refracting telescopes, and reflecting telescopes in which highly polished mirrors of glass or hard metal are used instead of lenses. The most convenient mounting for a telescope is as an *equatorial*, for then it can be pointed at any celestial body above the horizon at the time, and is turned by clockwork, so as to follow the stars in their apparent daily motion from east to west.

If a refracting telescope is used for celestial photography, its object-glass must be specially constructed to focus the actinic and not the visual rays of the ether.

2. *Instruments for measuring angles and time.*

(*a*) A transit circle.

(*b*) An altazimuth, or instrument for measuring altitude and azimuth. Sometimes it is necessary to measure the position of bodies not on the meridian, and the altazimuth is a convenient instrument for doing so.

(*c*) A micrometer. Most large telescopes are provided with some form of micrometer for measuring very small arcs between bodies in the field of view.

(*d*) A heliometer, for measuring somewhat larger arcs. So called because invented for measurements of the sun.

(*e*) A sextant, very useful at sea for measuring angular distances.

(*f*) An astronomical clock for the exact measurement of time.

(*g*) A chronograph, for keeping a record of the precise moment at which an observation is made.

3. *Astrophysical instruments*, for ascertaining the physical and chemical constitutions of the heavenly bodies.

(*a*) Spectroscopes, or light-analyzing instruments.

(*b*) A photometer, for measuring the intensity of the light of heavenly bodies.

(*c*) A bolometer, for measuring the intensity of the heating effects of heavenly bodies.

(*d*) A photographic camera, for giving a permanent and unbiased record of the results obtained by the above instruments.

Questions.

1. How is the position of a heavenly body defined—(*a*) in relation to the plane of the equator? (*b*) in relation to the plane of the ecliptic?

2. Explain the different systems of co-ordinates by which a star's direction is fixed in the heavens.

3. Explain the use of co-ordinates in fixing the position of a body on the celestial sphere, and define the terms—*altitude*, *azimuth*, *polar distance*, *hour-angle*, *right ascension*, *declination*, *latitude*, *longitude*. Which of these co-ordinates always remain constant for the same star?

4. How are the positions of the stars in the heavens determined? Name and describe briefly the instrument employed.

5. Describe the uses of the transit circle.

6. How is a transit circle used, and what information does it furnish?

7. How does a transit instrument enable us to check (*a*) a mean-time clock, (*b*) a sidereal clock?

8. What are the chief adjustments of the transit instrument, and how are they tested?

9. What is *parallax*, and under what conditions is the parallax of a heavenly body greatest? Show by some simple illustrations that as the distance of an object increases, its parallax lessens.

10. What is the meaning of "the parallax of the moon at Greenwich"? Define horizontal equatorial parallax, and annual parallax.

11. State how the distance of an object can be determined in miles when the parallax has been measured.

12. Describe how the distance of the moon is determined by observations made in the plane of the meridian. Why cannot the sun's parallax be accurately determined in this way?

13. What methods have been applied to determine the distance of the sun from the earth?

14. What is a transit of Venus? Explain how observations of this phenomenon help us in determining the distance of the sun.

15. Why is the method for finding the moon's parallax not available in the case of the sun? Show how the determination of the parallax of Mars at opposition leads to the determination of the sun's parallax.

16. How might the sun's parallax be determined by observations of the eclipses of Jupiter's satellites?

17. State the steps by which the sun's distance is determined, using the constant of aberration and the velocity of light.

18. What is meant by the constant of aberration, and how has it been determined?

19. Explain the *aberration of light*, and investigate the direction and magnitude of the displacement which it produces on the apparent position of a star.

20. The sidereal period of a certain asteroid is found to be 27 years.

Determine, by means of Kepler's third law, the distance of the planet from the sun, in terms of the earth's distance.

21. Distinguish between solar and stellar parallax. Describe Bessel's method of determining the annual parallax of a fixed star.

22. State the modern methods by which the distances of the stars are determined.

23. If the annual parallax be 0·2″, determine the distance of the star, taking the sun's distance to be 90,000,000 miles. Hence, deduce the distance of a star whose parallax is 0″·02.

24. Define parallax. What is the unit of distance employed in the determination of stellar parallax? And why?

25. By what methods are the diameters of the sun, moon, and planets in miles found?

26. Find the sun's diameter in miles, taking the sun's parallax as 8″·8, its angular diameter as 32′, and the earth's radius as 3960 miles.

27. Classify the various observations which are taken in astronomical observatories, and state the respective instruments which may be used for those observations.

CHAPTER XVII.

THE LAW OF GRAVITY IN THE SOLAR SYSTEM.

In the elementary work (p. 276) we stated Kepler's three laws of planetary motion deduced from observations, and showed how they were proved by Newton to be necessary consequences of his universal law of gravitation. It is therefore the attraction of gravity that holds the earth and all the other planets in their paths around the sun, and controls the movements of all the satellites round their primaries; and in the depths of stellar space beyond the solar system the same law holds good. It is the law of gravitation that enables us, from the movements thus produced, to calculate the masses of celestial bodies. We have shown that the tides are one of the effects of gravitation, and in the course of this chapter we shall show that certain disturbances (or perturbations) of the movements of the planets are effects of their mutual gravitational attractions and of the attraction of the sun and moon upon them.

Revolution of the Earth round the Sun.—In the *Elementary Physiography*, pp. 264–266, we gave the experimental proofs of the diurnal rotation of the earth, and at p. 273 of the same we stated the reasons for believing that the earth has an annual movement round the sun. The proofs of this motion are—

1. *The Annual Aberration of Stars.*—Careful measurements of the positions of stars show that they describe small ellipses in the course of a year. This motion cannot be a real one, for it is common, to all stars, takes place in the same time for all (a year), is always parallel to the plane of the ecliptic, the appearance of the orbit depends upon its distance from the plane of the ecliptic (see Fig. 141), and, finally, the major axis of the ellipse is always the same, viz. 41″, whether the star is relatively near or infinitely distant. The annual movement of the stars can therefore only be an apparent one, due to a

real motion of the earth in the plane of the ecliptic, and thus the phenomena of aberration afford one of the most con-

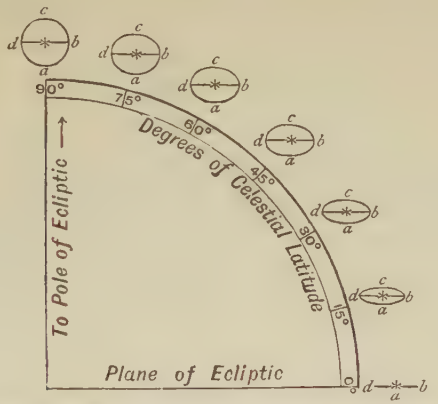


FIG. 141.—Aberration ellipses of stars in different celestial latitudes (after D. P. Todd), showing that they are always parallel to the plane of the ecliptic, that their major axis is always the same, namely, 41″, but that the length of the minor axis varies with the celestial latitude, being 41″ for a star in the pole of the ecliptic, and zero for a star in the plane of the ecliptic. (Contrast this figure with Fig. 139.)

vincing proofs of the annual revolution of the earth round the sun.

2. *The Annual Parallax of Stars.*—The stars (or at least the nearer ones) seem in slightly different directions at different times of the year, and this can only be explained as due to our change of standpoint, and thus we have another proof of the annual revolution of the earth.

3. *The Spectroscopic Proof.*—A slight shift in the lines of the spectra of some stars can be proved to be due to the movement of the earth relatively to the stars, and from the amount of shift the velocity of the motion can be determined.

Differences between Aberration and Annual Parallax.—As the reader may still have some difficulty in distinguishing between the aberrational and parallactic orbit of stars, we may here summarize their chief differences :—

Aberrational Orbit.	*Parallactic Orbit.*
1. Due to the earth moving while the light of the star is travelling to us.	1. Due to the apparent displacement of a star on the background of the heavens owing to a change in the earth's position in its orbit.

2. Same size for every star, semi-major axis being always 20″·5.

3. The star always seems a quarter of the ellipse ahead of the corresponding position of the earth (see Fig. 138).

2. Size depends upon the distance of the star (see Fig. 139). The semi-major axis is for no star as great as 1″, and for the vast majority of stars is too small to be measured.

3. The star always seems half of the ellipse ahead of the corresponding position of the earth (see Fig. 139).

Mass of the Sun.—By the law of gravitation, attraction is proportional to mass and inversely proportional to the square of the distance; or if we keep the distance constant, then the attraction is simply proportional to the mass. Expressing the attraction in terms of the number of feet it causes a body to fall, we get the following proportion :—

$$\frac{\text{mass of sun}}{\text{mass of earth}} = \frac{\text{no. of ft. fallen through in a sec. by a body 4000 miles from centre of sun}}{\text{no. of ft. fallen through in a sec. by a body 4000 miles from centre of earth}}$$

But the student, in his study of elementary physiography, will have learnt that all bodies allowed to drop near the earth's surface (*i.e.* 4000 miles from its centre) fall 16·1 feet in the first second. This is, therefore, the denominator of the right-hand member of the above equation. The numerator is easily got thus: Suppose the earth moves from E to E′ (Fig. 142) in a second, then EE′ is about $18\frac{1}{2}$ miles. But if the sun had not attracted the earth the latter would have moved in the straight line EC, so that CE′ or EA represents the distance that the earth falls towards the sun in a second, and, knowing that EE′ is $18\frac{1}{2}$ miles, CE′ can be calculated.[1] It comes out 0·00992 foot. Hence the earth falls this distance in a second towards the centre of the sun,

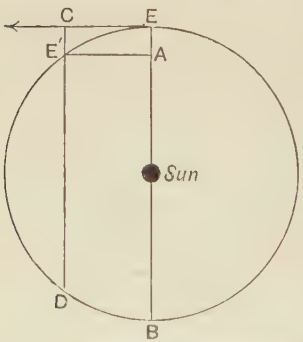


FIG. 142. The fall of the earth towards the sun in a second.

[1] The method of calculation is as follows. The earth's orbit is practically a circle, and CE is a tangent to it; therefore—

$$CE^2 = CE' \cdot CD \text{ (Euclid III. 36)}$$

$$\therefore CE' = \frac{CE^2}{CD}.$$

But EE′ is such a small fraction of the whole circumference (the

which is 93,000,000 miles off. How far would it have fallen in a second towards the sun's centre if the latter had been only 4000 miles off (*i.e.* 23,250 times nearer than it really is)? Obviously 0·00992 foot × $23{,}250^2$, for the attraction is inversely as the square of the distance. Hence the above equation becomes—

$$\frac{\text{mass of sun}}{\text{mass of earth}} = \frac{0{\cdot}00992 \times 23250^2}{16{\cdot}1}$$
$$= \text{about } 332{,}000$$
$$\therefore \text{ mass of sun} = 332{,}000 \text{ times mass of earth.}$$

Deductions from this—

(1) *Density of Sun.*—We have already shown that the diameter of the sun is 866,000 miles, or 109·5 times diameter of earth. But the volumes of spheres are as the cubes of their diameters, hence—

$$\text{volume of sun} = (109{\cdot}5)^3, \text{ or } 1{,}300{,}000 \text{ times volume of the earth,}$$

$$\text{therefore density of sun} = \frac{\text{mass of sun}}{\text{volume of sun}} \quad \text{(from the definition of density)}$$
$$= \frac{332000 \text{ mass of earth}}{1300000 \text{ volume of earth}}$$
$$= \tfrac{1}{4} \frac{\text{mass of earth}}{\text{volume of earth}}$$
$$= \tfrac{1}{4} \text{ density of earth.}$$

(2) *Force of Gravity at Surface of Sun.*—To compare this with the force of gravity at the surface of the earth, we must, according to the law of gravitation, divide the sun's mass (332,000) compared with that of the earth, by the square of its radius (109·5) compared with the earth's; therefore—

$$\text{force of gravity at surface of sun} = \frac{332000}{(109{\cdot}5)^2}$$
$$= \text{about } 27{\cdot}6 \text{ times force of gravity at surface of earth.}$$

Mass of the Planets.

1. *Planets with satellites*, such as Mars, Jupiter, Saturn, Uranus, and Neptune: In their case we can employ exactly

$\frac{1}{365\frac{1}{4} \times 24 \times 60 \times 60}$ part of it) that CE is practically the same length as the arc EE', namely $18\frac{1}{2}$ miles, and CD is practically the same length as EB, namely 186,000,000 miles. Therefore the equation just stated gives—

$$CE' = \frac{(18\frac{1}{2})^2}{186000000} \text{ miles}$$
$$= \frac{(18\frac{1}{2})^2 \times 5280}{186000000} \text{ feet}$$
$$= 0{\cdot}00992 \text{ foot.}$$

the same method as that just explained for the sun. For instance, Jupiter's second satellite revolves round it at a distance of about 268,000 miles (or 67 times the earth's radius, 4000 miles), and from this we can calculate the circumference of the satellite's orbit, and, knowing by observation the time required for a revolution, we can tell the distance the body moves in its orbit per second, and, as above, how far it falls towards Jupiter per second. This is found to be $1\frac{1}{15}$ foot. If the satellite were only 4000 miles from Jupiter, the amount of fall would be $1\frac{1}{15}$ foot $\times 67^2$; hence—

$$\frac{\text{mass of Jupiter}}{\text{mass of earth}} = \frac{1\frac{1}{15} \times 67^2}{16{\cdot}1} = \text{about } 310$$

that is, mass of Jupiter = about 310 times mass of earth.

Or we might employ Kepler's third law, which tells us that the cube of the distance of a planet from the sun divided by the square of its periodic time gives the same result for all the planets, for it depends simply on the mass of the central attracting body, the sun. Also, if we cube the distance of any satellite of, say, Saturn from the centre of the planet, and divide by the square of its time of revolution round Saturn, the quotient will be the same for every one of the nine satellites, since it depends only upon the mass of Saturn. Using this principle, we have—

$$\text{mass of planet} : \text{mass of sun} :: \frac{d^3}{t^2} : \frac{D^3}{T^2}$$

where T and D are respectively the planet's period and distance from the sun, and t and d the satellite's period and distance from the planet.

These four quantities can be found by observation, and thus we get the mass of the planet relatively to that of the sun, and therefore to that of the earth.

2. *Planets without satellites*, such as Mercury, Venus, and the planetoids: In this case the method that must be adopted is very much more difficult, and the result less accurate, for the mass can only be found by measuring the disturbance caused by the planet in the motion of some neighbouring body, and then calculating the mass that could at the planet's distance produce that disturbance. The mass of Venus, for example, is found by the perturbation she causes in the motion of the earth, and the mass of Mercury by his perturbing effect on Encke's comet, which sometimes approaches very closely to him.

The following are the masses of the planets given by M. Tisserand, with the earth's mass as unit :—

Mercury, 0·06	Jupiter, 310
Venus, 0·8	Saturn, 93
Earth, 1	Uranus, 14
Mars, 0·11	Neptune, 17.

Obtaining the densities in the usual way by dividing mass by volume, we find that Mercury is the densest of all ($1\frac{1}{3}$ that of earth). Venus, Earth, and Mars come next (the last mentioned being $\frac{3}{4}$ that of earth). Jupiter, Uranus, and Neptune have about the same density as the sun; while Saturn, the least dense of all, is only $\frac{1}{2}$ of that density, or $\frac{1}{8}$ the density of the earth.

Mass of the Moon.—Although the moon is so near to us, it is more difficult to accurately determine its mass than that of the most distant planet in our system. As the moon has no satellite, we must determine its mass by indirect methods as in the case of Mercury and Venus. Thus, the disturbing influence of the moon on the motions of the earth (causing nutation and lunar precession) can be measured, and from this we can, by very difficult calculations, find what mass could at the moon's distance produce those effects.

The method, however, most easily understood is that based on the fact that it is not the centre of the earth that moves in an ellipse round the sun, but the common centre of gravity of the earth and moon. In ordinary everyday language we speak of the moon revolving round the earth once a month, whereas in reality they each month move together as one body round their common centre of gravity, which lies in the line joining their centres, and is, as we shall see, so near to the centre of the earth that no great error is caused by the popular conception of it as being actually at the earth's centre. It is this point also that moves in the ellipse round the sun in accordance with Kepler's laws. Its position can be found. Suppose it to be at G (Fig. 143), in the line joining the centre of the earth, E, and of the moon, M; then, if the position of G be known, we can tell the mass of the moon, for—

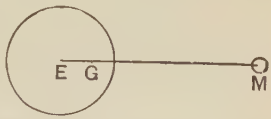


FIG. 143.—E, centre of earth; M, centre of moon; G, the common centre of gravity of earth and moon.

$$\frac{\text{mass of moon}}{\text{mass of earth}} = \frac{EG}{MG}.$$

The fact that it is G, and not E, that describes the orbit round the sun causes a small monthly displacement of the sun in east or west longitude. Fig. 144 will help to make this plain. At new moon, the centres of the earth, moon, sun, and the centre of gravity of the earth and moon are all in the same straight line, and therefore the apparent displacement of the sun is zero. The same is the case at full moon. But when the moon is at its first quarter, the line EM is at right angles to GS, and hence, relatively to

the centre of the earth, the sun is displaced a little towards the east, and the amount can be measured. It is found to be 6″·3 (and at third quarter the moon is on the opposite side of the earth from that shown in the figure, and the sun is displaced 6″·3 in west longitude); that is, the angle ESG is 6″·3. And the angle ESA is the parallax of the sun, and is therefore 8″·8. But when angles are very small they are to each other in the same ratio as the sides opposite to them, therefore—

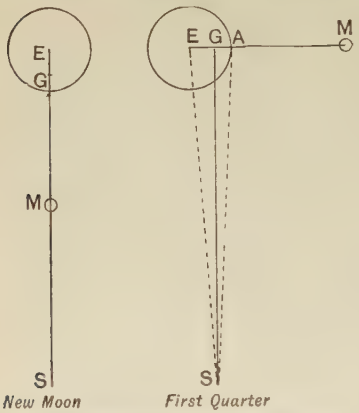


FIG. 144.—To illustrate the monthly displacement of the sun, S, in longitude.

$$\frac{EG}{EA} = \frac{6{\cdot}3}{8{\cdot}8}$$

whence, knowing the length of the earth's radius, EA, EG comes out about 2830 miles. But EM is 238,840 miles, so that EG is about $\frac{1}{81}$ of GM, and therefore, as stated above, the mass of the moon is $\frac{1}{81}$ of the mass of the earth.

Mass of the Earth.—So far we have only explained how to compare the masses of the sun, planets, and moon with that of the earth; it is, therefore, of great importance to determine the mass of the earth in pounds or tons, for then the absolute masses of the other heavenly bodies can at once be deduced.

A number of methods of finding the earth's mass have been tried, but this is not the place in which to give an account of each of these. They all employ the same principle, viz. comparing the earth's attraction on a mass A with that of a known mass at a known distance from A. Of course the difficulty in every instance lies in determining the attraction of the latter body for A, for with bodies of ordinary dimensions such attraction is extremely small. Some of them, such as the plumb-line or "mountain method," carried out by Maskelyne at Schiehallion in 1774, and Airy's pit method, carried out at the Harton Colliery, near Shields, in 1854, are now chiefly of historical or theoretical interest.

At p. 260 of *Elementary Physiography* we gave an outline of Cavendish's torsion-balance method. Professor C. V. Boys,[1] using a greatly improved Cavendish apparatus, has made one

[1] For an account of his method, see *Nature*, vol. L. pp. 330, 366, 417.

of the most reliable estimates of the earth's density and mass. The whole instrument used by Professor Boys is no larger than an ordinary galvanometer. For example, the large balls of the Cavendish apparatus, weighing over 1 cwt. each, are in Boys's instrument replaced by balls $1\frac{3}{4}$ lb. each, and the small balls used by Cavendish, weighing $1\frac{3}{4}$ lb. each, are replaced by small weights of 15 grs. each. The 6-foot horizontal beam connecting the small balls is replaced by one $\frac{5}{8}$ of an inch long.

The great trouble that Cavendish experienced was disturbance due to differences of temperature within the containing case; for suppose one side of the case to be warmer than the other, then this would cause the air next it to be rarefied and rise, while the air on the cooler side would descend, and the currents thus produced would cause deflections of the beam. By greatly reducing the dimensions of the instrument, Boys has almost entirely eliminated these disturbances. But the chief feature of Boys's apparatus is its great sensitiveness, and this he has secured by using quartz fibres of extreme fineness for supporting the beam and small balls. The fibres have great tenacity and almost no elastic fatigue (p. 4), and so sensitive are they to torsion that an attraction of $\frac{1}{10,000,000}$ part of a grain acting on the small balls produced a deflection of more than 10 feet on the scale, and forces 2000 times as small as this could be measured. With this instrument Boys found the mean density of the earth to be 5·527 times that of water.

Another modern method of finding the mass and density of the earth was tried with much success by Professor Poynting[1] at Mason Science College, Birmingham. From each end of the beam of a most sensitive balance he suspended a small sphere weighing about 21 kilograms, and consisting of an alloy of lead and antimony, the surface being gilded to protect it from atmospheric action. Then a large sphere of the same substance weighing 153 kilograms was moved by a turn-table first under the one small sphere and then under the other, so that the beam of the balance was inclined first the one way and then the other, because the weight of the small ball under which the large one was for the time placed was increased, being attracted downwards both by the earth and the massive sphere. The amount of inclination was measured,

[1] *The Mean Density of the Earth.* By J. H. Poynting, D.Sc., F.R.S. (Griffin & Co.).

and magnified 150-fold by a pencil of light reflected from a mirror attached to the beam of the balance, and the increased weight producing the deflection was determined by "riders" of known weights. This increase of weight was the attractive force of the large sphere for the small one, and from this he calculated what the attraction would have been had the large ball been the size of the earth; and, finally, from the ratio of this to the attraction of the earth for the small ball (viz. its weight), he obtained the mass of the earth relatively to the known mass of the sphere of the same size consisting of the alloy. Then dividing the mass of the earth by its volume, he calculated that the mean density of the earth was 5·4934 times that of water.

The mass of the earth is six thousand millions of millions of millions of tons, that is, 6 with 21 zeros after it, or 6×10^{21} tons—a number quite beyond our comprehension.

Perturbations.—As yet we have studied only two motions of the earth, viz. its diurnal rotation and annual revolution. But besides these there are slight irregular motions of the earth, called perturbations, due to the attraction of the sun, moon, and other planets. The chief perturbations are Precession of the Equinoxes, and Nutation.

Precession of the Equinoxes, and Method of determining it.—If accurate measurements of the position of a star are made in the equinoctial and ecliptic systems, it is found, even after the necessary corrections are made for refraction, aberration, and parallax, that three of these co-ordinates are continually changing by a very small amount year after year. The minute annual changes in declination and right ascension are different for different stars, but the celestial longitude is found to increase annually 50″·24 in the case of every star, while celestial latitude is the only one of the four co-ordinates that remains constant. If we examine Fig. 129, p. 254, we see that the only way of explaining this is by supposing the First Point of Aries, A, to move 50″·24 westwards or backwards to A′ along the ecliptic each year, for this would cause the celestial longitude AH of each star to increase 50″·24 per annum, but it would cause no alteration in the celestial latitude HS; it would, however, cause a slight change in the right ascension AG, and in the declination GS. It would, moreover, affect the time of return of the equinoxes, for the sun starts from A at the vernal equinox and seems to go round the ecliptic counterclockwise, or in the direction ADLF, and in order to

return to the First Point of Aries it has not to go to A, but only to A′. It therefore, between one spring equinox and the next, performs 50″·24 less than a complete circuit of the ecliptic. The time it would take to describe the remaining 50″·24 is 20 minutes, so that the equinoxes come back sooner or *precede* their time by 20 minutes, and hence the phenomenon is called *the precession of the equinoxes.*

Cause of Precession of the Equinoxes.—The motion of the earth giving rise to precession has been aptly compared to that of a spinning top. If the top when not spinning were placed in the position represented in Fig. 145, the force of gravity acting along CD, through its centre of gravity C, would at once cause it to fall to the ground. But if it be rapidly rotating it will not fall, but the upper end E of the axis AE will describe a circle round AB, the perpendicular to the ground at the point, and AE will describe a cone round that line. What holds good in the case of the peg-top is also true of the colossal earth. Let PQpE (Fig. 146) represent the earth; then, since the equatorial diameter EQ is 26 miles longer than the polar diameter Pp, we may regard the earth as a sphere (represented by the dotted circle PApB) surrounded by a ring of protuberant matter. The attraction of the moon M on the spherical part passes exactly through the earth's centre C, and will, therefore, not affect the position of the equator. It is different, however, with the protuberant part, for the moon will attract the nearer side AQ of it more than it does the farther side BE, and will consequently tend to twist the equatorial diameter EQ into the plane CM, that is, into the plane of the moon's orbit, which, as we shall see, is nearly the plane of the ecliptic. In an exactly similar way, the difference of the sun's attraction on the near

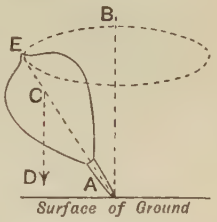


FIG. 145.—When a top is spinning it does not fall, but its axis describes a conical motion round a line, AB, perpendicular to the ground.

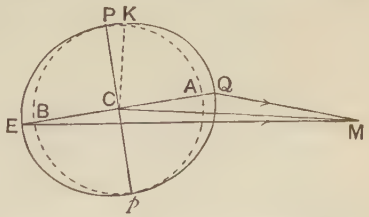


FIG. 146.—To show how lunar precession is due to the difference of the moon's attraction on the near and distant side of the earth's equatorial protuberance. Similarly for solar precession.

and far side of the equatorial protuberance will tend to twist the earth's equator into the plane of the sun's orbit, *i.e.* the ecliptic. But, as in the case of the spinning top, the earth's rotation prevents this, and the result is that the earth's axis describes a conical motion round a line passing through the earth's centre and perpendicular to the ecliptic, just as the top's axis does about the perpendicular to the ground. Hence the celestial pole P describes a circle with radius $23\frac{1}{2}^\circ$ (equal to the obliquity of the ecliptic) round K, the pole of the ecliptic, just as the summit E of the top does round the upper end B of the perpendicular to the ground. Observe that the obliquity of

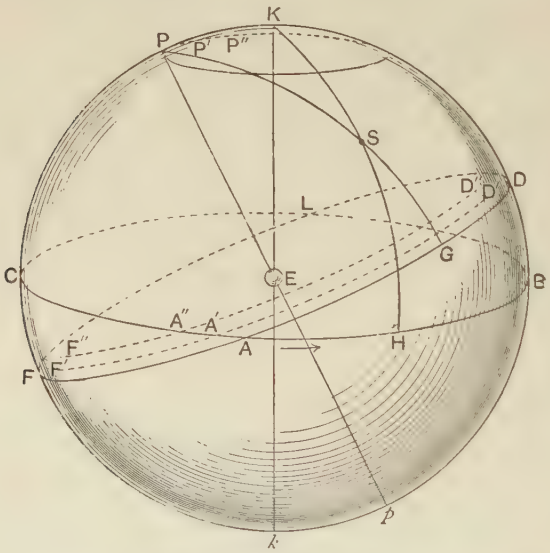


Fig. 147.—To illustrate the backward motion of the equinoctial points owing to the gliding of the equinoctial round the ecliptic.

the ecliptic ($23\frac{1}{2}^\circ$) does not alter, for the earth's diameter during the motion continues to make the same angle with the ecliptic ($66\frac{1}{2}^\circ$), just as the top's axis continued during its conical motion to make the same angle with the ground.

In Fig. 147, let PKDB*p*k*F*C represent the celestial sphere, ABLC the ecliptic, and K its pole; then these do not alter their positions. Let ADLF represent the equinoctial, and P its pole.

We have explained that P describes a circle PP′P″, etc., round K, and hence it carries the equator with it into the successive positions F′A′D′, F″A″D″, etc. We see that the angles BAD, BA′D′, BA″D″ are equal, that is, the obliquity of the ecliptic does not alter. But the equinoctial point A has a westward or retrograde motion on the ecliptic to A′, A″, etc., the amount of which is 50″·24 per annum, so that in about 25,800 years $\left(\frac{360^\circ}{50''\cdot24} = 25{,}800\right)$, A will have slipped backwards right round the ecliptic and returned to its present position again, and each year the sun, going round the ecliptic in the direction of the arrow, will describe 50″·24 less than a complete circuit in travelling from the First Point of Aries back to it again ; therefore the equinox precedes its time by 20 minutes, and hence this perturbation is called *precession of the equinoxes*, or *lumi-solar precession* as it is due to the combined disturbing action of the moon and sun.

The following experiment described in Prof. D. P. Todd's *New Astronomy* may help the reader to a more complete comprehension of precession.

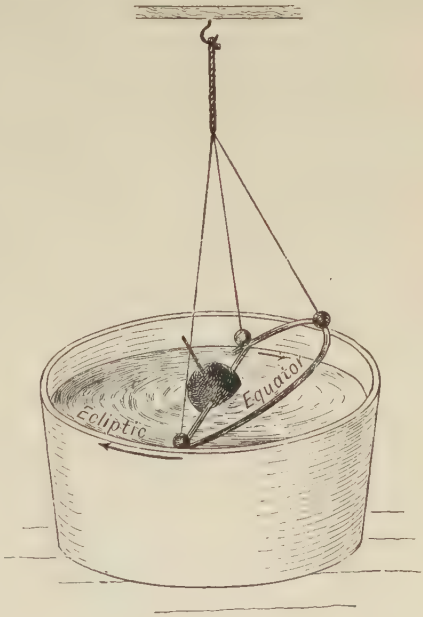


Fig. 148.—Experiment to illustrate precession.

Expt. 38.—Over a tub nearly filled with water suspend a barrel-hoop by three cords, two of which are equal in length and attached to the hoop at opposite ends of a diameter (Fig. 148). The third cord, a few inches shorter than the other two, is tied to the hoop midway between them. To load the hoop, fasten three weights of 1 lb. each at these same points. Gather the upper ends of the three cords together at a few feet above the hoop, and tie them to a right-hand-twisted cord a few feet long. To represent the earth

with its axis perpendicular to the hoop, pass a short wire through any spherical object easily obtained, and support the sphere in the centre of the hoop by a cross-piece nailed to the hoop at the two points indicated in the figure. Lower the hoop into the water until it is immersed to the knots of the two longer cords. These knots represent the equinoctial points, the hoop represents the equinoctial or celestial equator, and the surface of the water the plane of the ecliptic. Adjust the shorter cord so that the hoop is inclined about $23\frac{1}{2}°$ to the surface of the water. Then release the hoop, and the twisted cord will undo itself, and the hoop will turn round in the direction of the arrows, and the motion of the two opposite knots will correspond to the backward motion of the two equinoctial points on the ecliptic, and the wire will be observed to describe a conical motion as the earth's axis does.

Comparison of the Precessional Effects of the Sun and Moon.—If the above explanation be compared with that given for the tides, it will be seen that the action of the moon and sun in causing precession is precisely similar to their action in causing tides, for, taking the case of lunar precession, it is due to the difference of the moon's attraction on the near and the far side of the equatorial protuberance, just as lunar tides are due to the difference of the moon's attraction on the waters on the same and the opposite side of the earth as itself. In fact, in Fig. 146 we might regard the protuberant portions of the earth outside the sphere represented by the dotted circle as tides firmly fixed to that sphere, and hence we have no difficulty in concluding that lunar precession is two and a half times as great as solar.

This can be shown also by the same method of calculation as on p. 150, for the difference of the moon's attraction on the nearer and farther side of the earth's equatorial protuberance is proportional to—

$$\frac{0{\cdot}0123}{59^2} - \frac{0{\cdot}0123}{61^2}.$$

The corresponding difference for the sun is—

$$\frac{332{,}000}{23249^2} - \frac{332{,}000}{23251^2}.$$

Therefore—

$$\frac{\text{lunar precession}}{\text{solar precession}} = \frac{\dfrac{0{\cdot}0123}{59^2} - \dfrac{0{\cdot}0123}{61^2}}{\dfrac{332000}{23249^2} - \dfrac{332000}{23251^2}} = \frac{5}{2} \text{ approximately.}$$

The Effects of Luni-solar Precession may be summarized as follows:—

1. *A slow conical motion of the earth's axis round the axis of the ecliptic*, completed in about 25,800 years.

2. *The celestial pole describes a circle of radius* $23\frac{1}{2}°$ *round the pole of the ecliptic.* Hence every bright star on or near this circle is in succession the Pole Star during the 25,800 years. For example, at the time of Hipparchus (156 B.C.), when these positions were first observed, our present Pole Star (called *Polaris*, or *α Ursæ minoris*) was 12° away from the celestial pole. At present it is a little less than $1\frac{1}{2}°$ away from the pole, and this will go on diminishing until about 2100 A.D., when it will be $\frac{1}{2}°$. The celestial pole will then recede from Polaris, but after 25,800 years it will again be the Pole Star.

3. *A westward or retrograde motion of the equinoctial points along the ecliptic* at the rate of 50″·24 per annum, so that they make the complete circuit of it in 25,800 years. It is this backward motion of the equinoctial points to meet the advancing sun that causes the equinoxes to *precede* their time or recur 20 minutes earlier than they otherwise would.

4. *The signs of the zodiac do not now lie in the constellations of the same name.* The zodiac is the belt of the heavens 8° on each side of the ecliptic, and this belt is occupied by 12 constellations called the constellations of the zodiac, and the positions of the sun in the ecliptic at the four seasons are called the signs of the zodiac. At the time of Hipparchus the sun was in the constellation of Aries at the spring equinox, of Libra at the autumnal equinox, of Cancer at the summer solstice, and of Capricornus at the winter solstice; but since then the annual backward motion of 50″·24 has accumulated to 30°, so that each sign has "backed" into the constellation west of it, that is, the First Point of Aries is now in the constellation of Pisces, the First Point of Libra is in Virgo, the sign of Cancer is in Gemini, and of Capricorn in Sagittarius.

It will be easily understood from Fig. 147 that 12,900 years hence the northern summer will take place, not when the sun is at B, but at C, that is, when the earth is at perihelion, and winter when it is in aphelion, and this will make the summer warmer in the northern hemisphere and the winter colder.

5. *Changes in the co-ordinates of stars.*

(*a*) The latitude HS (Fig. 147) of a star does not alter, for the ecliptic ABLC does not alter its position.

(*b*) The longitude AH of any star increases annually by the amount AA′, which is 50″·24.

(*c*) The right ascension AG will evidently be slightly increased each year. For example, the R.A. of Sirius increases about 2·65 seconds of time per annum.

(*d*) The declination GS evidently alters from year to year, the average annual increase in the case of Sirius, for instance, being 4″·6.

Hence celestial charts and star catalogues give only the right ascensions and declinations of stars at a specified epoch.

The greatest alteration that can take place in the declination of any star is 47° *in* 12,900 *years.* For example, we may suppose that at present the Pole Star is at the celestial pole; but in 12,900 years our present Pole Star will be 47° away from the celestial pole, for the latter will have moved to the opposite side of the circle round K (Fig. 147) —that is, the polar distance of the present Pole Star will have altered 47°, and therefore its declination will have altered the same amount.

6. *The tropical year is* 20 *minutes shorter than the sidereal year*, for the tropical year is the time in which the sun moves from A round to A′, whereas the sidereal year is the time in which it returns to A again.

Nutation.—If the precessional forces were uniform then the celestial pole would, as we have seen, describe a circle of $23\frac{1}{2}°$ radius round the pole of the ecliptic. But the precessional forces are not constant, they vary periodically for reasons just about to be explained, and the consequence is that the celestial pole "nods" in and out a little from the circle, hence the name nutation (Lat. *nuto*, "I nod"). When the precessional forces increase, they tilt the equatorial protuberance of the earth slightly towards the ecliptic—that is, they cause the celestial pole to "nod" towards the pole of the ecliptic, or move slightly in from the circle mentioned; and when the forces decrease, the celestial pole moves a little out from the circle.

We might distinguish three cases of nutation, having periods respectively of (*a*) a year, (*b*) a month, and (*c*) 19 years. (*a*) The precessional effect of the sun is greatest at the two solstices, when our luminary is farthest north or south of the earth's equatorial protuberance, whereas at the equinoxes the solar effect is zero, for the sun is then right over the equator and therefore will have no tendency to twist the equatorial protuberance into the plane of the ecliptic. (*b*) In a similar way the moon causes a monthly nutation, for its precessional influence vanishes twice a month when it is crossing the plane of the equator, and is a maximum when the moon is farthest north or south of that plane. (*c*) The lunar nutation, however, with a period of 19 years is by far the most important, and we shall now briefly describe its cause.

The moon's orbit is inclined to the ecliptic at an angle of $5° 9'$, and cuts it at two points called the nodes; also, just as the nodes of the earth's orbit move westwards round the ecliptic in 25,800 years, so, for a similar reason, the nodes of the moon's orbit move westwards round the ecliptic in 19 years. Let us confine our attention to the ascending node of the moon's orbit—that is to say, the point at which the moon crosses the plane of the ecliptic in going from south to north. The letters in Fig. 149 correspond to those in Fig. 147, that is, ABLC represents the ecliptic, and ADLF the equinoctial. At some time during 19 years the moon's ascending node must coincide with A, the First Point of Aries, and then the moon's orbit (a small part of which is indicated by the line AX) will make with the celestial equator an angle of $18° 21'$

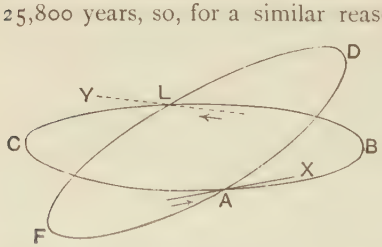


Fig. 149.—The retrograde motion along the ecliptic of the nodes of the moon's orbit.

for angle BAD is 23° 30′, and angle BAX is 5° 9′, therefore XAD is their difference, or 18° 21′. But in $9\frac{1}{2}$ years the moon's ascending node will have moved westwards till it coincides with L, and the moon must be moving in the direction indicated by the arrow at LY, since it is moving as before from south to north of the plane ABLC at an angle of 5° 9′. Then it is seen that the inclination of the moon's orbit to the celestial equator is 28° 39′ (23° 30′ + 5° 9′).

Now, when the moon's node is at L the moon produces nearly twice as much precessional effect as when at A, and hence, as explained above, the celestial pole moves inwards a little from the circle when the moon's node is at L, and a little outwards from it when at A. The amount of deviation from the circle is, however, very slight, viz. 9″·2 on either side. Hence the path of the celestial pole round the pole of the ecliptic is not a perfect circle; there are slight ripples on it much smaller than those indicated in Fig. 150, for there are 25,800 ÷ 19, or nearly 1400 of them round the whole circumference.

Effects of Nutation.—1. The obliquity of the ecliptic fluctuates 18″·4 in 19 years, for this obliquity is equal to the arc KP (Fig. 150), and as P threads its way out and in from the circle,

Fig. 150.—To illustrate nutation. K is the pole of the ecliptic; P, the celestial pole; the dotted curve represents the circle in which P would move owing to precession alone, and the wavy curve is the path in which P moves in consequence of precession and nutation combined.

the arc KP becomes alternately 9″·2 greater and less than its mean value.

2. The declinations of bodies change the above amount (18″·4) in a period of 19 years, for as the earth's axis nods alternately towards and away from the pole of the ecliptic, the celestial equator moves up and down the same distance, and declination, which is measured from it, must fluctuate also.

3. Because of nutation, the annual amount of backward movement of the equinoctial points alternately increases and

decreases from its average value of 50″·24. But the right ascension and longitude of stars are measured from the First Point of Aries, and therefore their rate of annual change must alternately increase and decrease.

It was from the 19-yearly variation in the declination, right ascension, and longitude of stars that nutation was discovered by Bradley as early as 1728.

Questions.

1. Give some of the reasons for concluding that the law of gravity controls the motions of bodies in the solar system.
2. State the methods by which the rotation and revolution of the earth have been demonstrated.
3. Since the sun attracts the earth, explain, by the parallelogram of forces, why the earth does not fall into the sun.
4. Describe the apparent movements of the stars depending upon (*a*) the earth's rotation on its axis; (*b*) the earth's revolution round the sun.
5. If the earth's equator were perpendicular to the plane of the ecliptic, what changes would this give rise to in (*a*) the apparent movements of the stars; (*b*) the seasons; (*c*) the length of day and night?
6. Show that, owing to aberration, a star in either pole of the ecliptic appears to describe a circle, and that a star in the ecliptic appears to oscillate to and fro in a straight line during the course of the year.
7. On what stars is the effect of aberration or parallax to make them appear to describe (*a*) circles, (*b*) straight lines?
8. Describe a method of comparing the mass of the sun with that of the earth.
9. Compare the density of the sun and the force of gravity at its surface with the corresponding quantities in the case of the earth.
10. How can the mass of a planet be determined by observations of its satellites?
11. How can the mass of Jupiter be found?
12. How would you compare the superficial gravity upon a planet with the force of gravity at the earth's surface, if you knew the mass and diameter of the planet?
13. How does the law of gravitation enable us to find the mass of the moon?
14. It is said that the moon revolves round the earth; is this strictly true?
15. State the mass and volume of the moon, and show how the density of the moon can be determined from the values you give.
16. Taking the moon's mass as $\frac{1}{81}$ that of the earth, show that the attraction which the moon exerts upon bodies at its surface is only about $\frac{1}{6}$ that of gravity at the earth's surface.
17. State the methods used in determining the density of the earth, and describe fully one of them.
18. Give an account of recent observations in connection with the density of the earth.
19. What is meant by "luni-solar precession"? Describe the action of sun and moon in causing the precession.

20. Give a general description of precession. Does precession change the position of (*a*) the equator, (*b*) the ecliptic among the stars?

21. How do observations with the transit instrument enable precession to be determined?

22. State some of the results of the precession of the equinoxes.

23. Describe the causes which produce the precession of the equinoxes, and its effect upon the R.A., and declination, and latitude, and longitude of stars.

24. What is the greatest change in the declination of a star caused by the precession of the equinoxes? Give a statement how the conclusion is arrived at.

25. The mean right ascension of Sirius on January 1, 1847, was 6 h. 38 m. 25 s., and on January 1, 1877, 6 h. 39 m. 44 s. Explain the cause of this alteration.

26. Where is the constellation Aries now in relation to the intersection of the ecliptic and equator, and why is it removed?

27. What are the lengths of the sidereal, tropical, and anomalistic years, and how are the differences in the lengths accounted for?

28. Describe *nutation*. What is the cause of lunar nutation?

29. How does nutation affect the obliquity of the ecliptic? Mention some of its other effects.

CHAPTER XVIII.

THE PHYSICAL CONSTITUTION OF THE SUN.

We have already shown how to find the sun's distance, mass, density, and volume. We have also learned to look upon the sun as the great store of radiant energy [1] from which is derived the motive-power for all physical and human activity on our globe. We shall now study in more detail the nature of this great central orb with which our earth and the other planets are so closely connected in origin, life-history, and destiny.

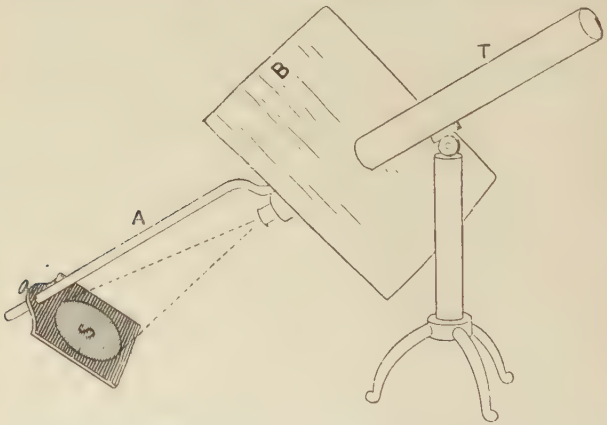


Fig. 151.—Diagram to illustrate how the details of the sun's surface may be examined without danger to the eye, and by a number of persons at the same time. T represents the telescope used. It forms an image, S, of the sun's disc on a sheet of paper supported by a frame at right angles to the axis of the telescope. This frame can be slid backwards or forwards as required on a support, A, attached to the tube of the telescope. B is a large sheet of cardboard preventing the direct rays of the sun from falling on the paper.

How to observe the Sun's Surface.—While examining the sun's surface with a telescope, precautions must, of course,

[1] See *Elementary Physiography*, p. 48.

be taken to protect the eye from injury. For this reason large telescopes are provided with a special solar eye-piece called a helioscope, which allows only a small part of the sun's rays to reach the eye. With ordinary instruments a darkened glass may be placed over the eye-piece; but this is liable to be broken by the intense heat focused upon it, and should this happen while the eye is at the telescope, the retina may be permanently injured. The safest plan is to project the sun's image on a screen placed in front of the eye-piece, and this method has the additional advantage that by it a number of persons can view the sun-spots and other details of the sun's surface at the same time. To prevent the direct light of the sun from falling on the paper, fasten a piece of cardboard two or three feet square round the tube of the telescope. The white piece of paper on which the image falls might be held in the hand; but a better way is to fasten it to a light frame, which can be slid backwards or forwards as necessary along a wooden rod rigidly attached to the tube of the telescope, and so that the sheet of paper is always at right angles to the axis of the telescope (Fig. 151).

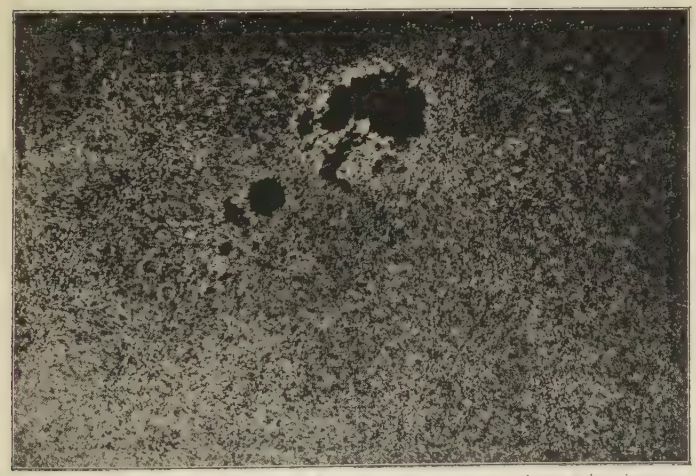


FIG. 152.—Photograph of a portion of the sun's photosphere, showing its rice-gram structure, and one large sun-spot and several smaller ones at a time of maximum number of sun-spots. (By permission of M. Janssen.)

Another method of examining the sun's surface is by means of photographs. This has been done with the best

results by M. Janssen of Meudon observatory, near Paris. He uses wet collodion plates, which have a much smoother surface than the ordinary dry films, and allows exposures of only from $\frac{1}{200}$ to $\frac{1}{1000}$ part of a second. The light of the sun is focused on the plate by means of a small telescope, whose eye-piece is, however, replaced by an enlarging lens, and thus he is able to produce photographs 15 inches in diameter, showing the smallest details of the part represented.

The Telescopic Appearance of the Sun's Surface.—The bright surface of the sun seen with the naked eye is called the photosphere, *i.e.* sphere of light. To the unaided eye it seems uniform in texture; with a telescope of low magnifying power it looks like rough drawing-paper; while with a powerful instrument it is seen to be made up of a darkish background sprinkled over with bright masses of irregular shape, giving the surface a mottled appearance resembling snow-flakes on a grey cloth. Nasmyth described the bright markings as like willow-leaves—that is, elongated in shape and pointed at each end. Near a sun-spot they have this form, but the name *rice-grains*, first applied to them by Secchi, better describes their general appearance (see Fig. 153). The grains usually measure from 400 to 600 miles each way, and with powerful telescopes they can, under favourable conditions, be resolved into smaller *granules*. The darkly shaded portions between the grains are generally marked with little dark dots called *pores* or *punctulations*. In addition to the rice-grains, there are much larger bright streaks seen, measuring from 1000 to more than 40,000 miles long and from 1000 to 4000 miles broad. They are called *faculæ* (*i.e.* little torches), and occur here and there over the greater portion of the sun's disc, but are most numerous in the neighbourhood of great dark portions called sun-spots, which are, in fact, often intersected by them.

From the rapid changes seen to take place in all these markings, it is evident that the photosphere is a mass of glowing gas. The rice-grains are just the tops of the white-hot clouds composing the sun's surface, and near a spot they get drawn by the disturbance into filaments resembling willow-leaves, which by their intersection form a rude thatch-like structure, as shown in the figure. The faculæ are ridges of luminous gas rising high above the general level and protruding through the denser portions of the sun's atmosphere. This is proved by the fact that when a facula passes to the edge of the

FIG. 153.—Drawing by Prof. S. P. Langley, showing the general "rice-grain" structure of the photosphere, and the "willow leaf" or "thatch-straw" structure in the neighbourhood of a spot. (From Orchard's *Astronomy*.)

sun's disc, it is seen as a little tooth-like projection, and to appear thus it is calculated that it must be at least 225 miles high, that is 45 times the height of the highest mountain on the globe.

The Appearance, Nature, and Size of Sun-spots.—A typical sun-spot consists of a dark more or less rounded centre called the *umbra*, within which a still darker *nucleus* can sometimes be seen. The umbra is surrounded by a region of half shade called the *penumbra*, made up of filaments directed radially inwards, and often showing a thatchwork pattern (see Fig. 153).

There is little doubt that spots are saucer-shaped cavities in the photosphere, and that the different shades represent different depths.[1] This is proved by the fact that spots on the edge of the sun have on several occasions been seen as notches, but especially by the change in the appearance of a spot as it is carried by the rotation of the sun across the visible hemisphere. When a typical spot is near the centre of the disc, its umbra is nearly central (Fig. 154), and as it is moved towards the edge of the disc the penumbra becomes broader on the outer edge and narrower on the inner, and when the spot has very nearly reached the edge the inner margin of the penumbra disappears altogether, as if concealed behind a bank.

FIG. 154.—Proof that sun-spots are depressions, from the change in the appearance of the same spot near the sun's centre and edge.

EXPT. 39.—Blacken the centre of a saucer, and then, holding its face towards the pupils and at the level of their eyes, move it in front of the class from one side of the room to the other, and ask the pupils to sketch the varying appearance of the dark centre and sloping sides.

Very small spots may have a diameter of only about 1000

[1] In 1774 Dr. Wilson, of Glasgow, gave a paper to the Royal Society demonstrating, from observations made on the great spot of 1769, that spots are cavities. Before that they had generally been supposed to be clouds floating in the sun's atmosphere. It should, perhaps, be stated that recent investigations by Mr. Howlett, M. Sykora, and others seem to show that spots are not in every case depressions below the general level of the photosphere, but are sometimes due to accumulations of absorbent material floating above that brilliant envelope.

miles. A spot as large as 27,000 miles can be seen with the naked eye at sunset or through fog as a minute black speck. Spots are sometimes twice this size. The largest one yet measured was in 1858. It was nearly 150,000 miles in diameter, and covered about $\frac{1}{35}$ of the entire surface of the sun. The most remarkable spot in recent years was one which, in February, 1892, reached the extreme dimensions of 162,000 miles by 75,000, and had an area of about 3000 million square miles.

It is difficult to determine the depth of sun-spots, but according to competent authorities it seldom exceeds 2500 miles and is generally between 500 and 1500 miles.

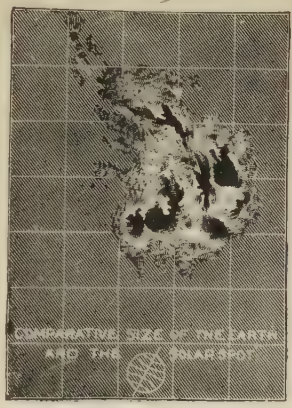


FIG. 155.—The great sun-spot of April 19, 1892, at 3.30 p.m. Length, 2′; breadth, 1′ 15″; area, about 1,093,500,000 square miles. (From *Knowledge*.)

The Duration, Distribution, and Periodicity of Sunspots.—Some spots last only a day or two, but the average duration may be given as two or three months. The spot we have just been describing was first seen in the middle of November, 1891, and was finally lost to sight in the middle of May, 1892. A spot which appeared in 1840 survived for nearly eighteen months. The first indication of a spot is generally a little black dot, which rapidly increases in size, and it is only after this is fairly well developed that the penumbra makes its appearance. Some spots take weeks to reach their full dimensions, while others only take a few hours. As the end of a spot draws near, the material of the surrounding photosphere seems to crowd in upon the umbra (see Fig. 155), appearing, as Secchi says, "to fall pell-mell into the cavity," filling it up, and leaving a group of faculæ to mark for a short time the place where the spot existed.

Spots do not occur on every part of the sun's disc. They are nearly always confined to two zones 30° broad extending from 5° to 35° on each side of the sun's equator (Fig. 156), and seem to be slightly more numerous in the northern zone than in the southern. Most spots occur about 15° on each

side of the sun's equator, and only one has been observed in as high a solar latitude as 50°.

Spots are not at all times equally numerous on the sun's surface. In some years several weeks may pass without a spot being seen, while at other times they appear in large numbers. In fact, spots occur in cycles. Once in about eleven years a maximum is attained, during which sun-spots are numerous and there is every indication of great turmoil at the surface of the sun. Then for six or seven years the spots slowly decrease in number to a minimum. After a period of repose, the perturbing forces once more break out, and in three or four years the spots are again at a maximum.[1] It is to be observed that the increase in activity is twice as rapid as the decrease; in other words, that the interval between a minimum and the succeeding maximum is only half of that between the latter and the next minimum. For example, the last maximum occurred in 1893, the last minimum in 1900, and the next maximum is due about 1904.

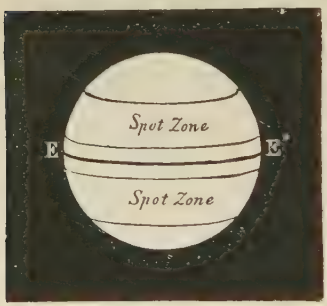


FIG 156.—The two zones of the sun's surface in which spots generally appear. (From Proctor's *Elementary Astronomy*.)

No satisfactory explanation has yet been given of the cause of these vicissitudes. Equally mysterious is the observed connection between the distribution of spots and their periodicity. After a minimum, spots break out at about latitude 30° or 35° on each side of the sun's equator; then, as the spots increase in size and number, they appear in lower latitudes. At the time of maximum, the mean latitude of the spot zones is about 16° or 18° north and south, and as the cycle comes to an end the last of the spots disappear at about solar latitude 8°. This is about thirteen or fourteen years after the commencement of the cycle. But already the new period has commenced, so that for two or three years—about the time of a sun-spot minimum—there are four distinct spot-zones, two about 8° on each side of the equator, due to the expiring disturbance, and two about 35°, due to the new series just begun.

[1] The period between two successive maxima or two successive minima is not always the same, but the mean period was stated by Wolf in 1852 to be 11·11 years, and this is the figure generally accepted.

Sir Norman Lockyer has thus described the phenomena of a sun-spot period:

"At a minimum period, the chief feature is a very great extension of the corona in the direction of the solar equator, and a wonderfully exquisite outcurving right and left at both poles.[1] The time between the minimum and maximum sun-spot periods is three or four years, and that from maximum to minimum seven or eight years, so that the sun increases in activity much more rapidly than it afterwards decreases in passing to the next minimum.

"During the maximum period all the solar forces are doing their utmost, and we see in prominences and spots indications of the most gigantic energies being at work. The ordinary prominences, instead of clinging to the equator, now occur most frequently at the poles. The faculæ are brighter and more widely distributed, and the spectrum of the chromosphere is richer in lines. The spots at this period occupy broad zones with mean latitudes of about 18° north or 18° south. There are no spots near the poles, and none near the equator; but large spots, indicating a state of violent agitation, surrounded by gigantic faculæ follow each other in these zones. Each of these indicators of solar activity is accompanied by a prominence. At this time, also, we note the greatest velocities of downrush in the vapours which form the spots, and of uprush in those which form the prominences. These changes are accompanied by corresponding changes in the corona. The streamers, instead of being limited to the equator or to mid-latitudes, exist in all latitudes, so that they practically extend from every part of the sun."

Do Sun-spots affect the Earth?—There is undoubtedly a relation between sun-spots and the earth's magnetism, though the exact nature of the connection is not yet known. When sun-spots are most numerous, magnetic disturbances or storms (see p. 152) are most strongly marked, and displays of the aurora borealis are most frequent and brilliant.

Some have attempted to prove that the temperature and pressure of the atmosphere, storms, and rainfall bear a relation to the number of sun-spots, but it cannot be said that an eleven-year meteorological cycle corresponding with the spot-cycle has yet been satisfactorily proved. Dr. Meldrum, of Mauritius Observatory, and others have brought forward statistics to prove that variations of atmospheric pressure and tropical cyclones are most frequent during the time of sun-spot maximum. The evidence, however, is not conclusive. Even more doubtful is the statement that at or near the maximum of sun-spots we have also the maximum amount of rainfall, for in some parts of the earth the rainfall is greater than usual at that epoch, and in others less.

Again, it is uncertain whether the temperature of the atmosphere is higher or lower during a sun spot maximum. Any

[1] These features are shown in Fig. 160.

effect produced must be very slight, for spots are by no means dark and cold. It has been estimated that they radiate about one-half as much heat and light as an equal area of the photosphere, and that when spots are most numerous they can, at the utmost, diminish the heat radiated from the sun $\frac{1}{100}$ part. Indeed, it is probable that the cooling effect of spots is more than compensated by increased radiation due to the accompanying disturbance of the photosphere.

In fine, observations will have to take place over a larger number of cycles, and we shall have to know more about the causes affecting meteorology before we can tell whether or not it is influenced by sun-spots. At any rate, it is now certain that if any connection does exist between the two sets of phenomena it is very slight.

The Movements of Sun-spots, and the Conclusions therefrom.

(1) When spots are watched from day to day, they are seen to change their positions. They come into view on the left-hand or eastern edge of the sun, move across the disc in about fourteen days, and then disappear from sight at the right-hand or western edge of the sun.

The obvious conclusion to be drawn from this is that the sun rotates round its axis in about 28 days (more exactly, 27·25 days), and that the direction of the rotation is the same as that of the earth, namely, *from west by south to east*, or *counter-clockwise* if viewed from above its north pole (see direction of arrows, Fig. 157).

But the true period of the sun's rotation is not 27·25 days,[1] for we must allow for the fact that the earth moves in its orbit round the sun in the same direction as the sun rotates, so that our luminary has to perform a little more than one rotation in order to bring a spot into exactly the same position again as seen from the earth. The time taken to describe this extra bit is almost two days, and the actual period of the sun's rotation is reduced to 25·35 days.

[1] This is termed the synodic period of the sun. Calling it S, and denoting the period of the earth's orbital movement by E, the sun's true period T can be obtained by the following relation (see also p. 320) :—

$$\frac{1}{T} - \frac{1}{E} = \frac{1}{S}$$

$$\text{or} \quad \frac{1}{T} - \frac{1}{365\cdot25} = \frac{1}{27\cdot25}$$

which gives T = 25·35 days.

Observations of sun-spots are the best, but not the only, method of proving the sun's rotation and determining its period. We have learned, at p. 74, that if a luminous body is approaching us, the number of ethereal vibrations per second received from it is increased, and therefore the lines in its spectrum are shifted a little towards the blue end of the spectrum; and, conversely, if it is receding, the lines are shifted a little towards the red end of the spectrum. Moreover, it was explained that from the amount of shift of the lines towards the one end of the spectrum or the other, we can calculate the rate of the luminous body's approach or recession. Now, if the spectrum of the left-hand or eastern edge of the sun (see arrows, Fig. 157) be examined, it is found that the Fraunhofer lines are slightly shifted towards the blue end of the spectrum, while for the western edge of the sun they are removed as much towards the red end. Hence we conclude that the left hand edge of the solar disc is always approaching us, and the right-hand edge receding, and that the sun is rotating from west by south to east, and the rate of rotation calculated by this method comes out the same as by the former one.

Finally, photographs of faculæ can now be daily taken, and they furnish an additional proof of the rotation of the sun.

(2) Observations show that the form of the paths of the sun-spots depends upon the time of the year.

In June spots go straight across the solar disc with a downward inclination of 7° 15′ to the plane of the ecliptic. In September they cross in paths concave upwards (to the eye of a northern observer). In December they again go straight across, but with an upward inclination of 7° 15′ to the ecliptic. In March the paths are again curved, but this time concave downwards.

The obvious conclusion to be drawn from these facts is that the sun's equator is inclined at an angle of 7° 15′ to the plane of the ecliptic, and hence that the sun is rotating round an axis inclined 82° 45′ to the same plane. In June and December the earth crosses the plane of the sun's equator, and therefore at these times we see both poles of the sun; but an examination of the upper part of Fig. 157 will show that in June the inclination of the sun's axis is 7° 15′ towards our right hand, and in December the same amount towards our left; and in these months the circular spot-paths, being viewed edgewise, appear straight and inclined downwards and upwards respectively, as shown in the lower part of the figure. In September the

sun's north pole is tilted 7° 15′ towards the earth, and the south pole is not seen by us, and an observer in the northern hemisphere views the circular paths slantwise, and they therefore appear concave upwards. In March the south pole of the sun is turned towards us, and the concavity of the paths is towards the south.

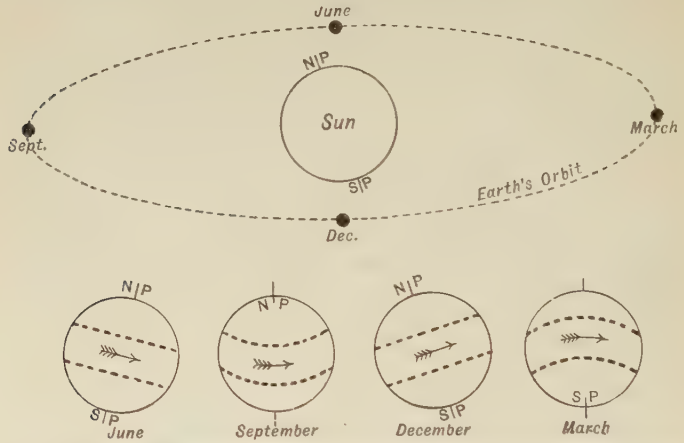


FIG. 157.—Diagram showing the sun's axis inclined 7° 15′ to the plane of the ecliptic, and the effect of this on the apparent paths of the sun-spots as viewed at different times of the year.

(3) Observations made on sun-spots or faculæ, or by the spectroscopic method mentioned above, reveal the strange fact that all parts of the sun do not rotate in the same time, and that the period increases with distance from the equator. At the sun's equator the time of rotation is 25·35 days, whereas spots in latitudes 20°, 30°, 40° take respectively 25·75, 26·5, and 27 days to go round the sun. It is obvious from this that the sun's surface is not rigid, for, if it were, parts in all latitudes would necessarily rotate in the same time. No perfectly satisfactory explanation of this strange rotation law of the sun has yet been given. Sir Norman Lockyer has suggested the following :—

"It is probable that the equatorial acceleration is connected in some way with the exchange of matter, which, if the sun is for the most part gaseous, as now seems likely, must continually be going on between the outside and inside of the globe. If the photosphere is formed of masses *falling*, such an effect would be a necessary consequence. If we suppose that the outrushing

streams of heated gas and vapour as they rise continue in the gaseous condition until they reach the summit of their ascent, and remain at this height long enough to acquire sensibly the rotation-velocity corresponding to their altitude, and that then the products of condensation resulting from their cooling fall downward, and thus constitute the photosphere, we should have precisely the actual phenomenon. The rotation-velocity of each visible element of the photosphere would be that corresponding to a greater altitude, and therefore greater than that naturally belonging to its observed position, and this difference would vary from the equator, where it would be a maximum, to the poles, where it would vanish."

Cause of Sun-spots.—This is another matter about which there is still much uncertainty. The following are some of the chief explanations that have been given :—

1. A theory strongly advocated by Sir Norman Lockyer and others is that vapours are constantly rising as convection currents from the sun's surface to the higher regions of the sun's atmosphere, where they are cooled and condensed. In this denser form they are brought down again by the sun's gravitational force, and plunge into his photosphere, causing a great cavity. The faculæ surrounding a sun-spot are due to the uprushes of gas produced by the splash.

Such falls of cooler material from the sun's atmosphere take place in all solar latitudes, and hence pores and veiled spots are found all over the sun's surface, but great sun-spots never occur beyond 45° north or south, because the sun's atmosphere is most extensive over a zone extending on each side of the sun's equator.

This theory also satisfactorily accounts, as we stated above, for the shorter period required by spots to go round the sun near its equator than in higher latitudes, for the sun's atmosphere is highest at the equator, and therefore the spot-forming material, having there a greater eastward velocity before its descent, will also, on falling into the photosphere, have a greater angular velocity.

2. M. Faye and many others support the theory that sun-spots are analogous to cyclones on the earth, the whirling motion being due to zones of the sun's surface near the equator rotating in a shorter time than those in higher latitudes, just as whirlpools are caused at a bend of a river by parts of the water moving faster than others.

There are two objections that seem to be fatal to this explanation. One is that spots do not usually exhibit the spiral structure they should according to this theory ; and the other is that, as Professor C. A. Young points out, the friction due to the difference of movement of the contiguous zones is not sufficient to produce such prodigious disturbances.

3. Father Secchi's theory, which in a modified form has been accepted by Young, is that spots are due indirectly to eruptions from beneath giving rise to the faculæ and prominences which usually surround a spot. The sun-spot itself is produced by this withdrawal of matter from below causing the photosphere in the neighbourhood to sink and the hollow so formed to be covered by cooler and darker vapours from above. What seems a serious objection to this theory is that according to it faculæ should be the precursors of a sun-spot disturbance, and only in two authenticated cases has this been observed.

4. The above three theories suppose spots to be depressions. An explanation of sun-spots on the hypothesis that they are not necessarily hollows is given in a footnote on p. 294.

The Sun's Surroundings.—That which we ordinarily see bounded by the photosphere is only a small part of the whole sun. The outer envelopes are visible to the unaided eye only during a total solar eclipse, when the moon comes exactly between the earth and sun and covers the dazzling photosphere. Then there is seen next the sun's surface a magnificent scarlet layer called the *chromosphere*. From this there spring fiery-red protuberances resembling tongues of flame, and called *red flames* or *prominences*. Outside the chromosphere there stretches, for a million miles or more, a sort of halo of silvery streamers called the *corona*. These envelopes are invisible at ordinary times, because their comparatively feeble luminosity is drowned by the intense light of the photosphere reflected and scattered in all directions through our atmosphere.

The Chromosphere and Prominences.—The gaseous envelope immediately above the photosphere is called the *chromosphere*, *i.e.* "sphere of colour," because when seen during a total solar eclipse it appears as a border of pink or scarlet. It owes its colour to the fact that it consists mainly of glowing hydrogen; but analysis of its light shows that it also contains sodium, magnesium, and helium [1]—an element not known on the earth till discovered in 1895 by Professor Ramsay in a rare mineral called clevite. The chromosphere is composed of close-set, upright filaments, and seems to consist of countless jets of glowing hydrogen rising through the interspaces between the photospheric clouds.

This envelope varies in depth from about 5000 miles to 10,000 miles; also its upper edge is not smooth, but jagged, and when the projections are great they are called *prominences*. Without having to wait for an eclipse, prominences can be viewed in full daylight by a spectroscopic method discovered

[1] Miss A. M. Clerke, in the volume on astronomy in the Concise Knowledge Library, says, "Helium is a colourless gas of about twice the density of hydrogen. Its peculiar qualities are shared only by argon, the new constituent of the earth's atmosphere. Both have unusual thermal properties; both are chemically inert. They refuse to combine with any other element, and thus stand apart from the round of multiform change involving the whole material world. Helium is nevertheless freely distributed throughout the universe. Even hydrogen itself is scarcely more ubiquitous."

simultaneously by Lockyer and Janssen; and in quite recent years Professor Hale, of Chicago, has introduced a method of photographing them (see Figs. 158 and 159). The consequence is that we now know a great deal about prominences. Their variety of forms and of structure is very great, but they are usually divided into two classes—

1. *Quiescent or Cloud Prominences.*—In outline they resemble cirrus or stratus clouds, and are often connected with the chromosphere by slender stems. They are found on all parts of the sun's surface, and often remain

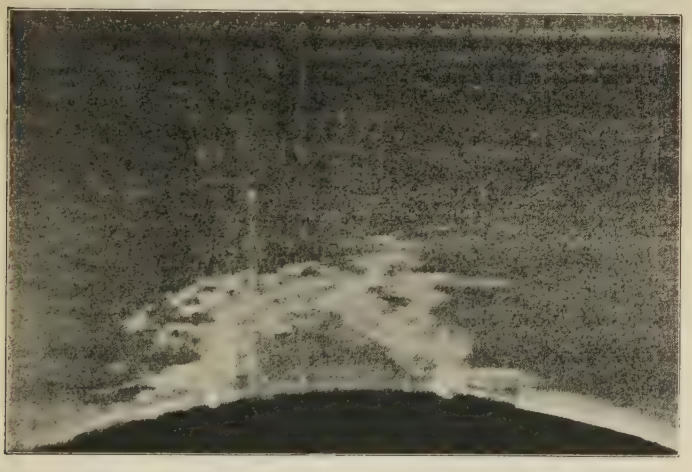


FIG. 158.—Quiescent prominence, photographed in full daylight by Professor G. E. Hale. (From *Astrophysical Journal.*)

nearly unchanged in appearance for days. Their size is enormous, their height varying from 10,000 to 100,000 miles. They are composed entirely of hydrogen and helium.

2. *Eruptive or Flame Prominences.*—They are usually not so large as the foregoing, and most frequently take the form of flames or separate filaments, but also assume a great variety of fantastic shapes. They are obviously the outcome of intense energy, and change their form so rapidly that it is no exaggeration to speak of them as veritable explosions. Detached filaments sometimes mount up at the rate of 100 miles a second, and on rare occasions four or five times as fast, and may reach 100,000 miles, 200,000 miles, or even nearly 400,000 miles from the chromosphere. For the most part they are observed only in the neighbourhood of active sun-spots, and last only a short time. They were called by Secchi "metallic prominences," because an analysis of their light shows that they are composed not only of hydrogen and helium, but also of iron, magnesium, sodium, and a number of other metals.

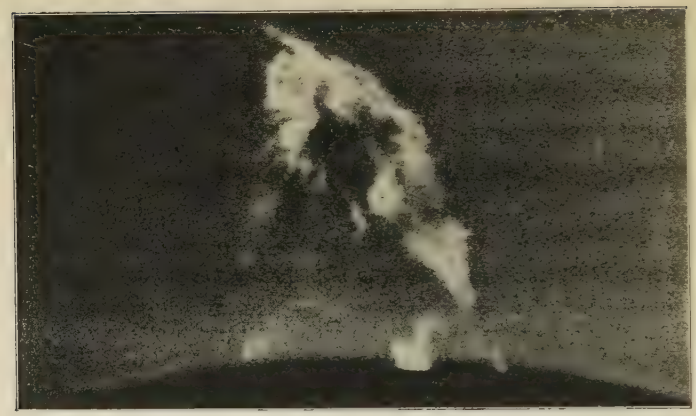


FIG. 159.—Eruptive prominence, photographed by Professor Hale. (From *Astrophysical Journal.*)

The Corona.—During total solar eclipses a bright halo of silvery light, giving about three times the light of full moon, surrounds the sun. It is called the corona. Its lower portion,

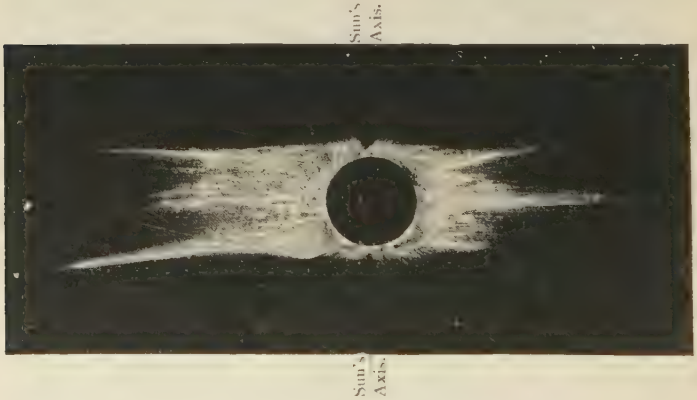


FIG. 160.—Drawing of the solar corona as seen in an eclipse on May 28, 1900, at a time of minimum number of sun-spots. Observe the inner corona and the great equatorial extension of the outer corona and its outcurving at the poles. (From *La Nature.*)

called the inner corona, is nearly circular in outline and of dazzling brightness, having a greenish pearly tinge or a silvery

whiteness which forms a beautiful contrast with the scarlet prominences projecting into it. At a height of about 100,000 miles it fades into the outer corona, much less brilliant, and

FIG. 161.—Photograph of an eclipse of the sun on May 17, 1882, at a time of maximum number of sun-spots. Observe that the corona is pretty equally developed in all directions. During the darkness a comet was seen near its perihelion passage. (By Professor Schuster's permission.)

extending at least one million miles from the sun. It consists of bright beams and streamers radiating outwards and separated from each other by dark rifts, in which the light is much less intense than elsewhere. The shape of the outer corona is

never exactly the same in two successive eclipses, but lengthened observations show that it undergoes a periodical change coincident with the eleven-year sun-spot cycle. In eclipses that have occurred at a minimum sun-spot epoch, it has been found that the corona is much less brilliant than at ordinary times, that it has great equatorial extensions, stretching sometimes nine or ten million miles above the spot regions, and that its polar streamers curve away like plumes in opposite directions (Fig. 160).

At a time of maximum spots, the corona is composed of short, bright, interwoven streamers pretty equally developed all round the sun (Fig. 161).

Nature of the Corona.—There is still much mystery regarding the exact nature and origin of this aureole of the sun, for attempts to examine or photograph it during daylight have as yet failed, so that only during total eclipses, occupying altogether a few hours in a century, can it be studied. At one time it was supposed to be due to something in the moon's atmosphere or in our own, but there is now no doubt that it is a true solar appendage, and shares in the rotation of that luminary. It is extremely tenuous, as is shown by the fact that comets have passed through it without being in the slightest degree disturbed. An analysis of the coronal light shows that it is derived from three sources—partly from incandescent solid or liquid particles, partly from photospheric light reflected to us by those particles, and partly from incandescent gas. This gas is chiefly hydrogen, and a supposed element which was named coronium because it was only known to exist in the corona.

The matter composing the corona may be partly of meteoric origin, but there is no doubt that it is also due to heated vapours rising from the photosphere, and that the small solid particles are formed by the condensation of this vapour in the higher and cooler portions of this solar envelope. The luminosity of the corona seems to be largely due to electric discharges through it, similar to those which cause auroral displays. In this way the vertical movements observed in the corona may be due to electric repulsion of gaseous matter from the sun, just as matter is repelled from the head of a comet, and to the downward attraction of solar gravity on the fine dust formed by the condensation of the vapours that have thus ascended.

The Sun's Light and Heat, and how they are maintained.—It is difficult to convey in words any idea of the luminosity of the sun. To express it in

popular language, the sun gives as much light as two and a half billions of the most powerful electric lights, or if the sky were covered with full moons their combined light would only be one-eighth of that of the sun, for 600,000 full moons would be required to equal the light of the sun.

The temperature of the sun is very difficult to ascertain, as is shown by the fact that estimates of it have ranged from 1500° to 5,000,000°. The results obtained in 1894 by Messrs. Wilson and Gray in England, and in 1892 by M. Chatelier in France, are considered the most reliable, and they come to practically the same conclusion, namely, if the sun's surface were as good a radiator as lampblack, then its temperature must be about 8000° C., or 8800° C. if we allow for the heat intercepted by the sun's atmosphere. No artificial heat on the earth exceeds 2200° C. What the temperature of the internal portions of the sun is we have no means of estimating. We know, however, that it must be higher than the above, and that from a consideration of this enormous heat and the low mean density of the sun (1·4 times the density of water), that body must be gaseous to the core. So great, however, is the pressure on the nucleus, that, although gaseous, it is denser than water, and viscous, and probably has about the consistency of pitch.

As viewed from the sun, the earth would only occupy $\frac{1}{2,128,000,000}$ of the whole sky, and hence only this part of the total radiations of the sun strikes our small planet, and yet even at our vast distance from the sun this small fraction of his heat, if it were uniformly distributed in all latitudes, would in a year melt a layer of ice 170 feet thick enveloping the earth.

Various explanations have been offered of the source of all this solar energy lavished so bounteously in every direction, but only two need be mentioned here as deserving our consideration. One theory is that the heat of the sun may be due to its continual bombardment by myriads of meteorites attracted towards it by gravity. A part of the heat may be produced in this way, but it is now believed that by far the greater part is generated in the way described by Professor Helmholtz and Lord Kelvin. Their theory is that as the gaseous sun cools it contracts, and that this shrinkage transforms the potential energy of separation into fresh supplies of heat. They estimate the life-period of the solar system at about thirty million years from origin to end, for they say that about twenty million years ago the gaseous material of the sun was too diffused to be giving out heat as it now does, and that five or ten million years hence it will have become solid and cold.

Questions.

1. How may the sun's surface be examined by means of a telescope?
2. Describe the appearance of the visible surface of the sun when observed through a good telescope.
3. Describe the telescopic appearance of a sun-spot, and tell what you know about the duration, distribution, and periodicity of spots.
4. What is a sun-spot? What changes take place in the solar latitudes at which they occur at different times?
5. State what you know about the nature of sun-spots, their periodicity, and distribution in latitude.
6. Give an account of the phenomena observed on the solar surface during a sun-spot period.

7. What terrestrial phenomena seem to be connected with the number of spots seen on the sun at different times?

8. What has been learned of the sun's rotation by the observations of spots?

9. What differences are observed in the apparent paths of spots across the sun at different times of the year?

10. How have the direction of the sun's axis in space, and the period of rotation been determined?

11. What peculiarities with regard to the rotation of the sun are brought out by observations of sun-spots?

12. What are the principal phenomena observed during a total eclipse of the sun?

13. Explain fully the terms corona, chromosphere, photosphere, faculæ, prominences. Why do we not see these when the sun is shining at ordinary times?

14. What has the spectroscope taught us respecting the chemical and physical constitution of the atmosphere of the sun?

CHAPTER XIX.

THE MOTIONS OF THE PLANETS.

The solar system consists of the great central body, the sun, and the train of miscellaneous attendants held captive by its overmastering attraction. We may enumerate the members of the system as follows :—

1. The *sun*.
2. Eight large *planets* revolving round the sun. In the order of their distance from the sun, their names are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune.
3. A large number of small planets, known as *minor planets*, or *asteroids*, revolving round the sun in orbits between those of Mars and Jupiter. About 500 are now known, and every year more are discovered.
4. The *satellites*, or moons, revolving round the planets. So far as yet discovered, Mercury and Venus have no moons, but the Earth has 1, Mars 2, Jupiter 5, Saturn 9 and 3 rings, Uranus 4, Neptune 1.
5. A number of comets. Seventeen such are known to be domiciled in the solar system, but probably there are many more.
6. A vast number of meteors travelling, often in swarms, in elliptic orbits round the sun.

Classification of Planets.—(1) Mercury and Venus travel round the sun in paths within the orbit of the earth, and are hence called *interior* or *inferior planets*. Mars, the asteroids, Jupiter, Saturn, Uranus, and Neptune have their orbits outside that of the earth, and are called *exterior* or *superior planets*.

(2) Mercury, Venus, the Earth, and Mars are sometimes called the *terrestrial* planets, because they are of pretty much the same size and density, and seem to be in pretty much the same physical condition as our globe. The outer quartette, Jupiter, Saturn, Uranus, and Neptune, are called the *major planets*, being giants in comparison, and are obviously in a very different physical condition from the other group separated from them by the asteroids.

Mean Distances of the Planets from the Sun, and

their Periods of Revolution round it.—The fifth column of the following table, taken mainly from Professor Young's *Lessons in Astronomy*, gives the diameters of the planets, but perhaps a better idea of their sizes relatively to the sun and to each other will be obtained from Fig. 163.

The time each planet takes to go round the sun is obtained

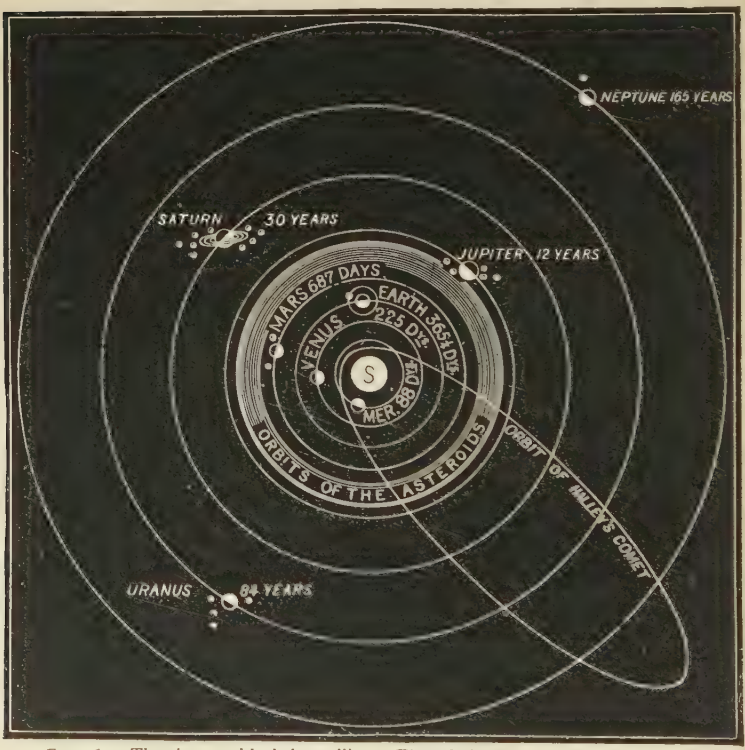


FIG. 162.—The planets with their satellites. The relative distances from the sun are not drawn to scale.

by observation, and the result is given in round numbers in the fourth column of the table. It was explained on p. 265 how, knowing the period of revolution of a planet, Kepler's third law enables us to calculate its mean distance from the sun. The distances are given relatively, and in miles, in the second and third columns.

Planets.	Distances from sun. (Earth's = 1.)	Mean distances from sun in millions of miles.	Periods of revolution round sun in years.	Diameters in miles.
Mercury . .	0·4	36	0·25	3000
Venus . .	0·7	67	0·63	7700
Earth . . .	1·0	93	1·0	7920
Mars . . .	1·5	141	1·8	4200
Asteroids. .	3·0±	280	3 to 9	10 to 490
Jupiter . .	5·2	483	11·9	87,000
Saturn . .	9·5	886	29·5	72,000
Uranus . .	19·2	1780	84·0	32,000
Neptune . .	30·1	2790	165·0	35,000

Bode's rule (so called because first published by an astronomer, Bode of Berlin, in 1778) is a remarkable mnemonic for remembering the distances of the planets from the sun. It is this:

Write down the following numbers, in which each except the second is double the one before it:—

0 3 6 12 24 48 96 192 384

Adding 4 to each, we get—

4 7 10 16 28 52 100 196 388

Dividing this by 10, we get—

0·4 0·7 1 1·6 2·8 5·2 10 19·6 38·8

and comparing these numbers with the second column in the above table, we see that they represent very nearly (except in the case of Neptune) the relative distances of the planets from the sun; hence, the earth's distance (93,000,000 miles) being known, we can, by a proportion sum, find approximately the distance of any other planet from the sun.

The Movements of Planets.—By watching markings on the discs of planets it is found that all the planets turn on their axes in the same direction as the earth does, namely, *from west by south to east*, or *counter-clockwise* if they could be viewed from above their north pole. The time of rotation is found by observing the time of the return of a marking on the planet's disc to the same position again as seen from the earth, and allowing for the forward motion of the earth in the interval. If no well-defined markings can be seen, the rotation period cannot be accurately found.

The largest planets rotate in the shortest time. Jupiter, the giant planet, rotates in 9 h. 55 m., Saturn in 10 h. 14 m., and there are indications that the time of rotation of Uranus is about the same as this, while that of Neptune cannot be determined because of its great distance. Next in order of length comes the earth with 23 h. 56 m. 4·09 s., very closely followed by Mars with 24 h. 37 m. 22 s. Following this at a long interval are Mercury and Venus, which seem to rotate in

the same time as they take to go round the sun, namely, 88 days and 225 days respectively.

The planets (Gr. *planetes*, "a wanderer") were so named because of their observed wanderings in the heavens, and their

FIG. 163.—Relative sizes of the sun and planets. The white disc represents the sun (866,400 miles in diameter), and the black discs represent, on the same scale, the planets in order, from Mercury on the left to Neptune on the right.

movements are satisfactorily explained on the hypothesis that, like the earth, they travel in elliptic orbits round the sun, situated at one focus of the ellipse in each case. They all travel round the sun in the same direction, namely, *from west*

by south to east, or *counter-clockwise*, if we suppose ourselves looking upon the system from the north side of the orbits. This kind of movement is called *direct*, whereas motion in the opposite direction is called *retrograde*.

So far as can be observed, all the satellites of the solar system rotate on their axes in the same direction as do the planets. Also, with one exception, their orbital motion round their primary is direct. The four moons of Uranus apparently move round it in a retrograde direction.

Inclination of Planets' Equators to their Orbits.—Observations of the movements of markings across the disc of a planet determine not only its period of rotation, but also, just as in the case of the sun, the direction of its axis in space. Only in the cases of Mars, Jupiter, and Saturn, however, are markings seen with sufficient distinctness to furnish perfectly reliable results, namely—

	Inclination of equator to orbit. ° ′
Earth	23 27
Mars	24 50
Jupiter	3 5
Saturn	26 49

But we saw in the case of the earth that the seasons on a planet are determined by the inclination of its equator to its orbit, hence from the above we know that there can hardly be such a thing as seasons on Jupiter, and that the seasonal differences on Mars and Saturn are somewhat more marked than on the earth.

Shape of Planets' Orbits and their Inclination to the Ecliptic.—By measuring the change in the sun's apparent diameter throughout the year it has been found that the earth moves in an elliptic orbit. Were it possible to make similar measurements of the sun's diameter from each of the planets in turn, it would be found that they too move in ellipses. This fact is expressed in what is known as Kepler's First Law of Planetary Motion,[1] viz. the orbit of each planet is an ellipse, the sun being situated in one focus of each ellipse.

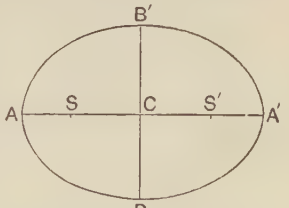


Fig. 164.—AA′ is the major axis of the above ellipse; BB′, its minor axis; C, its centre; S and S′, its two foci; and the fraction $\frac{CS}{CA}$, its eccentricity.

If C be the centre of an ellipse (Fig. 164), S one of its foci,

[1] See *Elementary Physiography*, p. 276.

and A an end of its major axis, then the ratio $\frac{CS}{CA}$ is called the eccentricity of the eclipse; that is—

$$\text{the eccentricity of an ellipse} = \frac{\text{distance from its centre to its focus}}{\text{semi-major axis}}$$

Now, the orbits of all the planets are of small eccentricity, that is, the paths are nearly circular. The eccentricity of the orbit of Mercury is about $\frac{1}{5}$, of Mars $\frac{1}{11}$, of Jupiter, Saturn, and Uranus about $\frac{1}{20}$, and of Venus and Neptune very slight.

The orbits of all the larger planets lie nearly in one plane. The angles that the orbits of Mercury, Venus, and Saturn make with the plane of the ecliptic are shown in Fig. 165, and the

FIG. 165.—Diagram showing the planetary orbits (excluding the asteroids) having greater inclinations to the ecliptic than 2°.

paths of the other four larger planets are inclined to the ecliptic less than 2° in each case.

The orbits of the asteroids vary much in their inclination to the ecliptic, but, taking the whole group, the average is about 8°, the greatest inclination being the orbit of Pallas, 34° 37′. The ancients confined their astronomical observations pretty much to the zone of the heavens 8° on each side of the ecliptic, beyond which the planets known to them never wandered, and they called this belt the *zodiac*.

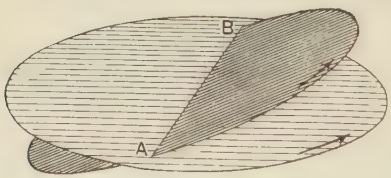


FIG. 166.—If the horizontal curve represents the orbit of the earth, and the other curve the orbit of another heavenly body, then A, at which the body passes to the north of the plane of the ecliptic, is called the ascending node, and B, at which it passes to the south of the plane, is the descending node, and AB is the line of the nodes.

The plane in which the earth's orbit lies is called the plane of the ecliptic, and if the orbit of a planet (or any other celestial body) is inclined to the earth's orbit, it must cut the plane of the ecliptic in two points which are called the *nodes* of the planet's orbit, and the line joining them is called the *line of the nodes*.

Positions of the Planets.—In consequence of the motions of the planets round the sun, they periodically come into line with the earth and sun, as shown in Fig. 167. When the three bodies (earth, sun, and planet) are in line, and the planet is on the same side of the earth as the sun, it is said to be in *conjunction;* and when the three are in line, but the planet

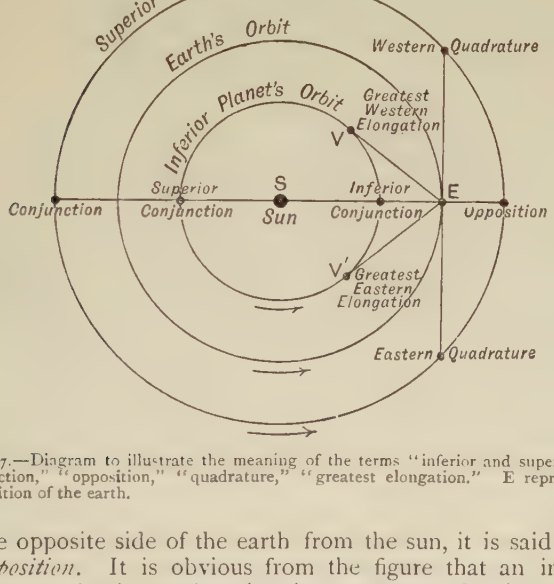


Fig. 167.—Diagram to illustrate the meaning of the terms "inferior and superior conjunction," "opposition," "quadrature," "greatest elongation." E represents a position of the earth.

on the opposite side of the earth from the sun, it is said to be in *opposition*. It is obvious from the figure that an inferior planet may be in conjunction in two ways; for it may be between us and the sun, and is then said to be in *inferior conjunction*, or it may be beyond that luminary, and is then in *superior conjunction*.

The angle between a line joining the centre of the earth and the centre of a planet, and a line joining the centre of the earth and the centre of the sun, is called the elongation of the planet. For example, in Fig. 167 the elongation of a planet at V is the angle VES, hence we might also define the elongation of a planet at any time as *its angular distance from the sun as observed from the earth*. When a heavenly body is in conjunction, its elongation is 0°, and it crosses the meridian at noon. When the

body is in opposition, it crosses the meridian at midnight, and its elongation is 180°. If the elongation of a celestial body is 90°, it is said to be in *quadrature*, and it crosses the meridian either at 6 a.m. or 6 p.m. according as it is in western or eastern quadrature. It will be apparent from the figure that the elongation of an inferior planet cannot be as great as 90°. Thus, for the inferior planet in the figure, the angle VES is called its *greatest western elongation*, and V'ES its *greatest eastern elongation*. The greatest elongation of Venus is 47°, and of Mercury 28°.

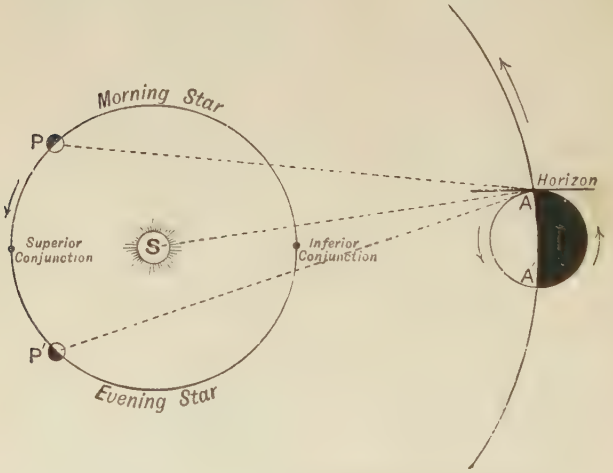


FIG. 168.—Mercury and Venus as morning and evening stars.

Inferior Planets as Morning and Evening Stars. — In latitudes like ours, in which the sun is south at noon, the right-hand edge of the sun is towards the west, and its eastern edge is towards our left hand.[1] It will be seen from Fig. 167 that Mercury and Venus between inferior and superior conjunction are to the right or west of the sun, and that from superior to inferior conjunction they are to the left or east of the sun. So long as they are in western elongation, they rise and set before the sun, and are *morning stars*: and when in

[1] In corresponding latitudes in the southern hemisphere the sun is north at noon, and the right-hand edge of the sun is its eastern one, and its left-hand edge its western one.

eastern elongation, they rise and set after the sun, and are *evening stars*. Fig. 168 shows this more fully. The tangent at the place A on the earth represents the horizon there, and as the horizon is carried round from A to A′ by the west-to-east rotation of the earth, the planet in position P will rise above the horizon and set below it before the sun and be a morning star, whereas at P′ the sun will rise and set first, and the planet will therefore be an evening star.

Venus is a striking object whether as a morning or evening star. The ancients knew that it was in both cases one and the same planet, although they applied to it different poetic names —Lucifer when a morning star, and Hesperus when an evening star.

The Orbital Motion of Planets as seen from the Earth—Direct and Retrograde Motion; Stationary Points.—If we could view the motion of any planet from the sun, it would be seen moving always eastwards amongst the stars in a nearly circular orbit. But the motion of a planet as seen from the earth is by no means so simple, for it is complicated by the fact that we are viewing it from a moving observatory.

If in Fig. 167 we suppose ourselves at E, viewing the counter-clockwise motion of the inferior planet, the latter will about the time of superior conjunction appear to move from right to left, *i.e.* eastwards amongst the stars, or *direct;* whereas about the time of inferior conjunction it will appear to us to move from left to right, *i.e.* westwards amongst the stars, or *retrograde*. There must be an intermediate point at which the motion of the inferior planet changes from direct to retrograde, and as then the planet appears to move neither eastwards nor westwards, it is called a *stationary point.*

From the same figure it will be seen that the motion of the superior planet at conjunction is *direct*, and at opposition is *retrograde*, for the earth and the planet are both moving round the sun in the same direction, but the earth is going round in a shorter time than the superior planet, and therefore is moving with a greater angular velocity eastwards; this makes the superior planet at opposition appear to go in the opposite direction, or *retrograde*. Between these two positions of the superior planet there must be a *stationary point.*

The general motion of a planet, then, is eastwards among the stars, but after a time it slackens and becomes stationary; then for a shorter period it appears to turn back and move

westwards, but by-and-by it becomes stationary again, and then resumes its eastward motion. *The middle of the arc of direct motion is always reached when the planet is farthest from the earth* (*i.e.* at superior conjunction), *and the middle of the arc of retrogression is reached when the planet is nearest the earth* (*i.e.* at inferior conjunction for an inferior planet, and at opposition for a superior planet).

If other planets moved round the sun in the same plane as the earth does, they would appear during their retrograde motion to move backwards along the same path as they advanced in. But the fact that the orbits of other planets are inclined slightly to the earth's orbit causes the planets to appear

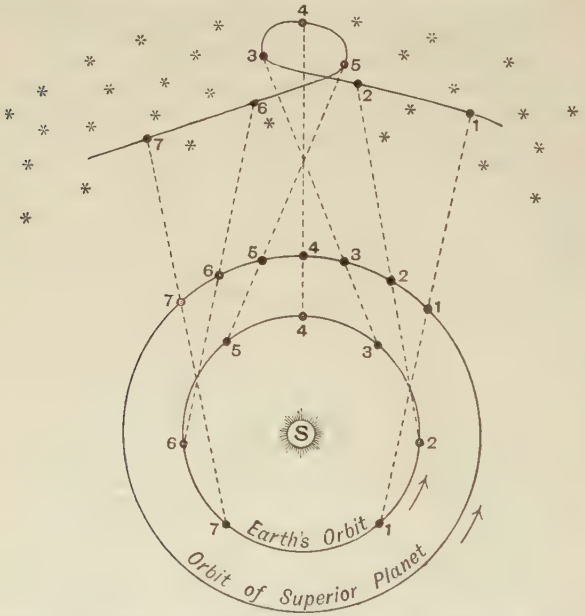


FIG. 169.—To explain the formation of a loop in a superior planet's path as seen from the earth.

to describe a loop during their retrogression. We shall briefly explain this for a superior planet. In Fig. 169, the inner circle represents the orbit of the earth, and the outer the orbit of an exterior planet, and the stars represent a portion of the zodiac. When the earth is successively at 1, 2, 3, 4, 5, 6, 7, the planet is simultaneously at 1, 2, 3, 4, 5, 6, 7 in its orbit. By following the directions of the dotted lines joining these corresponding positions, we see that when the earth is at 1, the planet will seem projected among the stars of the zodiac at 1 ; when the earth is at 2, 3, 4, 5, 6, 7, the

planet will appear to be at 2, 3, 4, 5, 6, 7 among the stars. The planet's orbit is inclined to the earth's orbit, so that if we suppose the planet in the positions 1, 2, 3, and 4 in its orbit to be moving farther and farther northwards of the plane of the ecliptic, and then to turn, and in positions 5, 6, and 7 in its orbit to be moving southwards towards the plane of the ecliptic again, then it will appear to move from 1 to 4 northwards among the stars as shown, and from 4 to 7 southwards; also the planet's apparent motion in the zodiac is direct from 1 to 3, retrograde from 3 to 5, and direct again from 5 to 7.

The Phases of Inferior and Superior Planets.—Telescopic examination of the inferior planets Venus and Mercury reveals that they pass through all the phases of the moon. At superior conjunction, they exhibit a fully illuminated disc (see A, Figs. 170 and 171). From superior to inferior conjunction they wane, and pass through all the phases, from full moon to new moon (Fig. 171), and pass during the other half of their motion through all the phases from new to full moon. At their greatest elongation, C, they appear as half-moon, and just before and after inferior conjunction they appear in the crescent phase D.

Superior planets are never between us and the sun, and therefore they cannot pass through all the phases of the moon. Indeed, from the fact that we are constantly within their orbits, we must always see more than half of their illuminated hemisphere. We see least of their bright surface when they are in quadrature, and then they exhibit the gibbous phase.

The Sidereal and Synodic Periods of Planets.—*The sidereal period of a planet is the time it takes to go exactly once round the sun*, i.e. the time it takes, as seen from the sun, to journey from conjunction with a fixed star back to it again. The synodic period of a planet is its period as viewed from the earth, *i.e.* it is the time between two successive conjunctions of the same kind, or two successive oppositions.[1] It is obvious that this is not equal to the sidereal period of the planet, because of the earth changing its position during the interval.

The synodic periods of planets are obtained by observation, and from them their sidereal periods are calculated as follows: The daily motion of the earth is $\frac{360^\circ}{365\frac{1}{4}}$, and the daily motion of a planet is $\frac{360^\circ}{P}$, where P is the number of days in its sidereal period. If the planet be an inferior one, then each day it gains on the earth $\frac{360^\circ}{P} - \frac{360^\circ}{365\frac{1}{4}}$. But if S be the synodic period of

[1] The moon has similarly two periods, namely, its sidereal period, in which it goes exactly once round the earth, and its synodic period, which is the interval between two successive full moons, or two successive new moons.

the planet, then it gains a whole revolution in this time, therefore its gain on the earth per day is $\frac{360°}{S}$. Hence—

$$\frac{360°}{P} - \frac{360°}{365\frac{1}{4}} = \frac{360°}{S}$$

$$\text{or } \frac{1}{P} - \frac{1}{365\frac{1}{4}} = \frac{1}{S}.$$

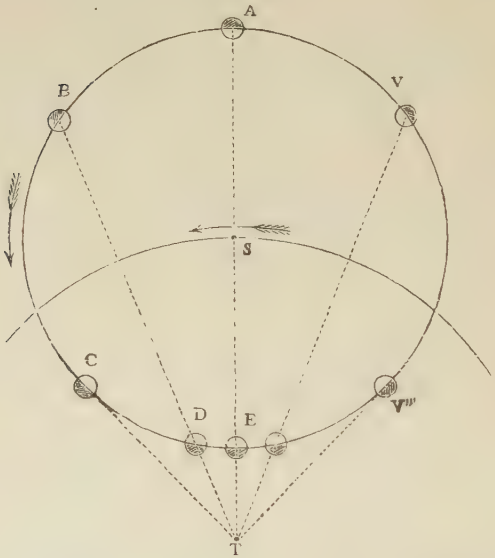


FIG. 170.—The positions of Venus with respect to the earth. T represents the earth; V, Venus; and S, the sun. The circle represents the orbit of Venus, and the large arc the apparent motion of the sun owing to the orbital motion of the earth. (From Ball's *Elements of Astronomy*.)

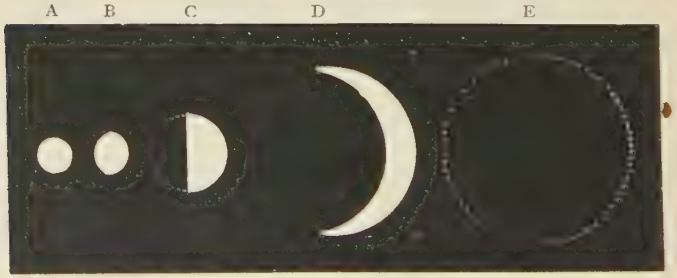


FIG. 171.—Phases of Venus and the variations in its apparent size in one half of its orbit (From Ball's *Elements of Astronomy*.)

In the case of a superior planet it is the earth that gains, and therefore the equation becomes—

$$\frac{1}{365\frac{1}{4}} - \frac{1}{P} = \frac{1}{S}.$$

For example, the synodic period of Mercury is observed to be 116 days,

$$\therefore \frac{1}{P} - \frac{1}{365\frac{1}{4}} = \frac{1}{116}, \text{ whence } P = 88 \text{ days.}$$

The synodic period of Mars is 780 days,

$$\therefore \frac{1}{365\frac{1}{4}} - \frac{1}{P} = \frac{1}{780}, \text{ whence } P = 686 \text{ days.}$$

Questions.

1. What bodies constitute the solar system?
2. State Bode's rule, and relate how it led to the discovery of the first asteroid (see p. 329).
3. What position does the earth occupy in the solar system? Explain the term "inferior planet," and show how the path of such planets appears at times to retrograde.
4. When is a planet an evening star, and when a morning star?
5. Show by means of a diagram the relative positions of Venus and the earth when Venus is (*a*) a morning star, (*b*) an evening star. State the position of Venus with regard to the earth and sun (*c*) at its stationary points, (*d*) at superior and inferior conjunction.
6. Describe the apparent motion of Venus relatively to the sun.
7. Why can Mercury only be seen near the sun, and how is it that Venus is never seen more than 47° away from the sun?
8. Describe and explain the looped path which a planet appears to describe among the stars.
9. Define fully, by diagram or otherwise, the meanings of the following terms: gibbosity, elongation, opposition, conjunction, stationary points, synodic period.
10. Distinguish between the sidereal and synodic period of a planet. How is the synodic period of a planet determined, and how can the sidereal period be determined in the case of (*a*) an interior planet, (*b*) an exterior planet?
11. Define the *sidereal* and *synodic period* of a superior or inferior planet, and find the relation between them. Calculate the synodic period of a superior planet whose period of revolution is thirty years.

CHAPTER XX.

THE PLANETS.

Mercury in a number of respects is an exceptional member of the solar system. Having a diameter of 3000 miles, it is the smallest of the eight principal planets; it has also got the least mass (about $\frac{1}{16}$ that of the earth) and the greatest density (a little greater than the earth's). It revolves round the sun in the shortest time, its year being 87·97 days. Its path is more highly inclined to the ecliptic than the other principal planetary orbits and is more eccentric, for while its average distance from the sun is 36 million miles, its actual distance varies from 29 to 43 million miles.

Its Atmosphere.—One of the most crucial questions as affecting the surface conditions of a planet is the presence or absence of an atmosphere. There is conclusive proof that Mercury is almost airless. When seen under good conditions by day, his colour is just like that of the pale moon which has no atmosphere. Also, when Mercury is just entering upon the sun's disc during a transit, there is no ring of light surrounding it, as is seen in the case of Venus under similar conditions, owing to sunlight shining through and illuminating its atmosphere. The spectroscope, however, seems to indicate absorption due to aqueous vapour; hence Mercury probably has an atmosphere like our own, but much less extensive and dense.

Its Telescopic Appearance and Period of Rotation.—When a superior planet is in opposition it crosses the meridian at midnight, and therefore at such a time we have an opportunity of examining its surface night after night during the whole period of darkness. It is not so with the two inferior planets. Mercury, for instance, is never more than 28° east or west of the sun, and as the earth rotates 15° per hour, Mercury is never above the horizon more than two hours after sunset or before sunrise. As an evening or morning star it is generally lost in the mists near the horizon, and is seldom distinctly visible to

the naked eye, and even in telescopes the details of its surface are very imperfectly seen. It is observed, however, to go through the same phases as the moon, to have a rose-coloured disc on which can be seen extremely faint markings of a brownish-red hue, and, according to the latest observations in America, the markings consist rather of lines than patches.

From the fact that these do not change their position from hour to hour, nor perceptibly from day to day, it is now believed that the planet always presents the same side to the sun—that is, takes the same time to rotate on its axis as it does to revolve round the sun (87·97 days), just as the moon rotates once while it revolves once round the earth.

Venus, our nearest planetary neighbour, in some respects closely resembles the earth. It is of nearly the same size, its diameter being 7700 miles, and its mass $\frac{4}{5}$ of the earth's; its mean density is almost the same as the earth's, being in fact 0·86 of that of the earth, and the force of gravity on its surface is almost exactly the same fraction of terrestrial gravity; and, like the earth, it has an extensive aërial envelope.

The mean distance of Venus from the sun is 67 million miles, but its distance from the earth varies from 26 million miles (93 − 67) at inferior conjunction to 160 million miles (93 + 67) at superior conjunction, and, in consequence, its apparent diameter varies from 11″ to 7″, as shown in Fig. 171.

Atmosphere of Venus.—At the beginning and end of a transit, when the planet is just entering on or leaving the sun's disc, its black surface is seen to be surrounded by a ring of light, owing to the refraction of sunlight by its atmosphere. For the same reason, when Venus is in the thin crescent phase, the horns of the atmospheric ring are seen to continue outwards and form a complete ring, or nearly so. From the amount of refraction produced by it, it is believed that the Cytherean atmosphere is nearly twice as extensive and dense as our own, and the spectroscope proves the presence of water-vapour in it.

The Telescopic Appearance and Period of Rotation of Venus.—With the aid of a telescope, it is found that Venus goes through all the phases of the moon (see Figs. 170 and 171). Although Venus comes nearer to us than any other planet, we as yet know comparatively little regarding the nature of its surface. One reason for this is that its greatest elongation is 47°, and consequently it is never more than fully three hours above the horizon after sunset or before sunrise. Another is that its brightness is so great as to dazzle the eye and render observations

of the details of its surface difficult. Only filmy, indefinite spots or markings covering large areas have been made out, and at the poles white patches, supposed by some to be snow or ice, have been observed. The latest observations of the planet are those of Mr. Lowell in 1896, and they led him to question the correctness of the above details. He saw no polar snow-caps, and he described the disc as "simply a design in black and white, over which is drawn a brilliant straw-coloured veil" (doubtless the planet's atmosphere). The markings seen were not spots, but broad belts often radiating from a centre. There is every reason to accept this description as correct, for the observations were made under exceptionally favourable circumstances in the clear air of Arizona; but the features he describes have not yet been seen from other observatories.

The indistinctness of the markings makes it exceedingly difficult to determine the period of rotation of the planet. Until 1890 it was believed to be 23 h. 21 m., but in that year Professor Schiaparelli, of Milan, brought forward strong evidence for believing that Venus, like Mercury, rotates once while she revolves once round the sun—that is, 224·7 days—and that its axis of rotation is nearly perpendicular to the plane of its orbit. Astronomers are not agreed on the matter, but a number of authorities on the subject have by their observations been led to the same conclusion as Schiaparelli, and altogether it seems probable that the long period is the correct one.[1]

Mars.—The diameter of Mars is 4200 miles. As its volume is $\frac{1}{7}$ and its mean density $\frac{4}{5}$ that of the earth, we see that it would take nine such spheres to make up the mass of our globe. The force of gravity on the surface of Mars is only 38 per cent. of its terrestrial value; that is, a body weighing 100 lbs. on the earth would only weigh 38 lbs. on Mars.

From observations of markings on its surface, we know that the planet takes 24 h. 37 m. to rotate, and that its equator is inclined 24° 50′ to its orbit. Its seasons must therefore resemble our own, except in being nearly twice as long (for Mars takes 687 days to go round the sun), and in receiving

[1] Owing to the comparative nearness of Mercury and Venus to the sun, the solar tides on them would be much greater than on the other planets, and the retardation of their rotation due to tidal friction would be greater also. They have, indeed, got so much slowed down in their rotation that they now always present the same face to the sun, while the earth and the other remoter planets will take a much longer time to undergo this amount of retardation.

less than half the light and heat that we do from the sun, because of the planet's greater mean distance ($141\frac{1}{2}$ million miles) from that luminary. Its seasons will also be considerably modified by the fact that the eccentricity of its orbit is so great that Mars is 26 million miles nearer the sun when in perihelion than in aphelion.

The Telescopic Appearance of Mars.—The best time to observe the surface features of Mars is when it is in opposition, for then it is on the meridian at midnight, and is on an average only $48\frac{1}{2}$ million miles ($141\frac{1}{2} - 93$) from us. Oppo-

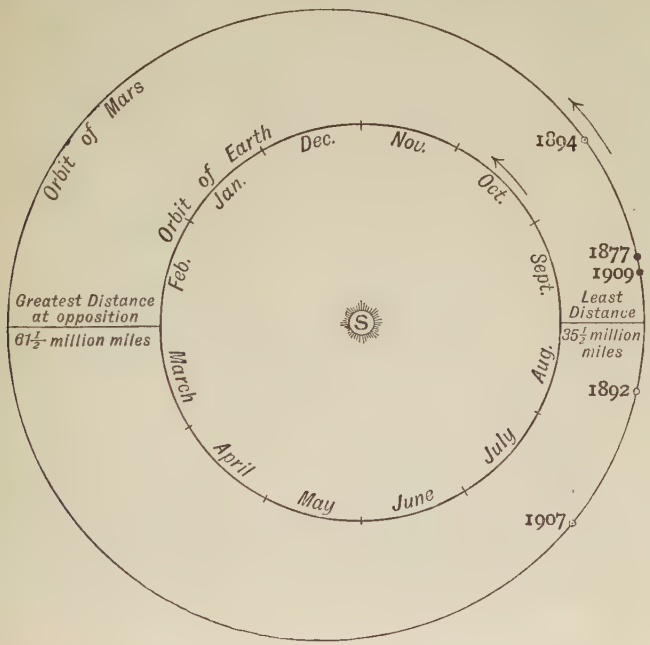


FIG 172.—To show that, owing to the eccentricity of its orbit, the distance of Mars from the earth is different at different oppositions. The positions of Mars in its orbit at several oppositions are indicated by the dates.

sitions recur at intervals of 780 days, but they are not always equally favourable, for owing to the great eccentricity of the planet's orbit, the above distance varies, as we have said, 26 million miles; that is, if Mars is in perihelion at the

time of opposition, we are only $35\frac{1}{2}$ million miles from it, and if in aphelion, the distance is $61\frac{1}{2}$ million miles. Fig. 172 will make this plain. The smaller circle represents the orbit of the earth, and on it are marked the positions of the earth during the various months of the year. The outer circle, described with a different centre, represents on the same scale the orbit of Mars. It will be seen that the most

FIG. 173.—View of Mars showing the canals and the lakes at their intersection. (From *Mars*, by Percival Lowell.) At the time when the drawing was made, longitude 120° of Mars was on the meridian.

favourable oppositions of Mars are those that occur about August or September, and the least favourable in February and March. The oppositions of 1877 and 1892 were very favourable, as will also be those of 1907 and 1909.

The disc of Mars is, as a whole, ruddy, but when viewed through a good telescope it is diversified with three shades of

colour—there are regions of a reddish or dull orange colour supposed to be land, parts of a dark greyish-green colour believed to be water, and patches of dazzling white at each pole. These are polar snowcaps, corresponding to those in our own arctic and antarctic regions, as is proved by the fact

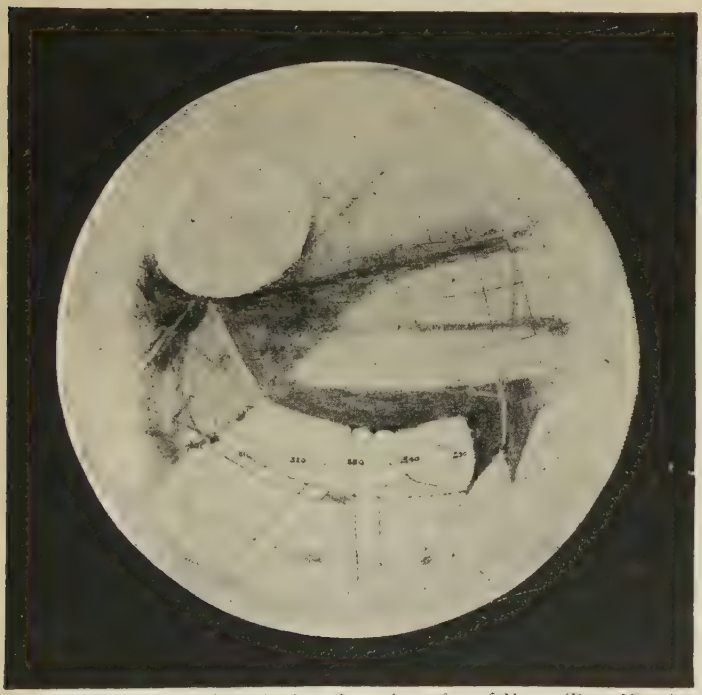


FIG. 174.—Showing several double channels on the surface of Mars. (From *Mars*, by Percival Lowell.) At the time that the drawing was made, longitude 330° of Mars was on the meridian.

that they are most extensive during the local winter, and shrink to a mere remnant as the summer advances.

On our globe there is almost three times as great an extent of water as of land, but on Mars there are about two and a half times as much land as water, and it is believed to have a much smoother land-surface than the earth's, as but few projections and irregularities are seen along the terminator (*i.e.* the boundary between bright and dark portion of the disc). The

continents are not sharply outlined, and extensive regions along their margins change colour periodically, as if subject to great inundations by the sea owing to the immense quantity of water set free by the rapid melting of the great polar snow-caps during the long Martian summer.

The chief peculiarity, however, of the surface of Mars consists in the way in which the land is intersected in all directions by a network of narrow water-channels called *canals* connecting the seas and of the same grey-green hue. They were discovered by Schiaparelli at the opposition of 1877, while he was making a trigonometrical survey of the planet. They run, as a rule, straight along great circles of the planet for an average distance of about 1200 miles (sometimes between three and four thousand miles), and with an average width of only about 30 miles. Where a number of canals intersect, there are sometimes oval or circular spots called *lakes* or *oases*. Now and then some of the canals are seen to be doubled, that is, have twin canals running exactly parallel to them, and at an average distance of about 200 miles from them (Fig. 174). This canal duplication is periodical, depending on the Martian seasons.

Some have been misled by the word "canals" into the belief that they are artificial and the work of human beings on Mars. No satisfactory explanation of them has yet been given, and, as their discoverer says, we must "trust to the courtesy of nature for some ray of light by which, in the future, to penetrate the mystery."

Atmosphere of Mars.—That this planet has an atmosphere similar in composition to our own, but not so extensive nor so dense, is proved in several ways. Occasionally white cloud-like appearances have been seen to veil for a time certain markings on the surface of Mars. Also Dr. Huggins and others have found in the spectrum of the planet absorption-lines due to water-vapour. The existence of an atmosphere is proved, too, by the slightly undefined appearance of the planet's terminator, whereas in the case of the moon, which has no atmosphere, the boundary between the illumined and dark part is perfectly sharp.

The distinctness with which we can see even the minute surface features of Mars is an indication of the thinness and tenuity of his gaseous envelope. Indeed, the density of his atmosphere cannot be greater than half that of our own, and is probably much less.

The two satellites of Mars were discovered by Professor Hall at Washington in 1877, and he called them Phobos and Deimos, because in the *Iliad* Panic and Fear are the attendants upon Mars, the god of war. From the amount of light they reflect, neither of them can be more than 10 miles in diameter. Phobos, the inner moon, is only 5800 miles from the planet's centre, and revolves round it in 7 hours 39 minutes—that is, less than one-third of the time that Mars takes to rotate. This is a unique phenomenon in the solar system, and because of it Phobos would, to an observer on Mars, appear to *rise in the west and set in the east*, and would go through all its phases three times between two successive risings. Deimos, the outer moon, is 14,600 miles from the centre of Mars, and revolves round it in 30 hours 18 minutes, during which period it changes four times from new to full moon.

The minor planets, or so-called asteroids, are a group of small planets revolving round the sun between the orbits of Mars and Jupiter.

Their Discovery.—When Bode's rule was published, there was a gap in the series between the two planets just mentioned, and this led astronomers to suppose that there must be an intermediate planet. So firmly was this believed that in 1800 Bode and other twenty-three astronomers agreed to make an organized and minute search in equal portions of the zodiac for the missing body. While this search was in progress, Professor Piazzi, of Sicily, on the first night of the nineteenth century (January 1, 1801), discovered a small planet in the exact position required by the law, and called it Ceres after the tutelary divinity of his native island. Within the next six years three others, named Pallas, Juno, and Vesta, were discovered, and since the middle of the century not a year has passed without the list being added to (the year 1896 added no fewer than 40), and now the total number discovered is nearly 500, and probably there are thousands more. The planetoid hunter has in recent years been greatly helped by photography. A region of the sky likely to contain them is photographed, with an exposure of two or three hours. The images of the stars are focused on the sensitive plate by a telescope, which follows the movement of the sky, and they come out, therefore, as sharp points of light; but if there be any small planets in that region, they are revealed by the trails they leave upon the plate because of their motion during the exposure. The planetoids used to receive mythological names, but, as these

are becoming exhausted, they are now designated by the number in order of their discovery, written with a circle round it, *e.g.* Hilda (153).

Their Orbits.—They all, without exception, travel round the sun in the same direction as the earth, but the orbits of no two coincide, nor even intersect. The mean inclination of their orbits to the ecliptic is 8°, that is, slightly greater than that of the orbit of Mercury. The orbit of Pallas has the greatest inclination to the ecliptic, viz. nearly 35°. Their mean distance from the sun is about 280 million miles. The nearest, Medusa (149), is 198 million miles, and Thule (279), the most remote, is 400 million miles from the sun, their periods being 3 years 40 days, and 8 years 313 days respectively. Their orbits are in many cases very oval, the eccentricity of some nine or ten being over 0·3.

Their Size and Origin.—Vesta, the brightest planetoid, is just visible to the naked eye when near opposition. But it does not seem to be the largest, for, according to Professor Barnard, of Yerkes Observatory, the diameters of the four largest asteroids are—

Ceres	485 miles.
Pallas	304 ,,
Vesta	243 ,,
Juno	118 ,,

The smallest, such as are now being discovered, are probably less than 10 miles across.

The aggregate mass of the planetoids is very small; Leverrier said that it could not amount to one-fourth that of the earth, and is probably very much less. The total mass of those as yet discovered is about $\frac{1}{6000}$ that of our globe; it is therefore probable that thousands, or even millions, remain undiscovered.

It was at first believed that the minor planets had their origin in the explosion of a single large planet, but this has been disproved, and the prevalent view now is that the gaseous material which ought to have condensed to form a single planet has, owing to some disturbing influence—probably the attraction of the neighbouring giant planet Jupiter—failed to do so, and has formed instead a crowd of separate bodies.

Eros.—In August, 1898, Dr. G. Witt, of Berlin, while searching photographically for minor planets, discovered, as he thought, one moving with a

more than usual velocity. When its orbit was calculated, the little body proved to be quite an exceptional one, for instead of travelling round the sun between the orbits of Mars and Jupiter, it was found that its path lies between those of the earth and Mars, and that its period of revolution is about 600 days (*i.e.* 80 days less than Mars takes). It is thus our nearest neighbour after the moon, and is therefore one of the most suitable bodies for determining the parallax of the sun by the method described on p. 262, and has indeed been already employed for this purpose. In accordance with the suggestion of its discoverer, the name Eros has been given to this important little body, and, from the analogy of the minor planets, it will be rather surprising if this new planet is the only one revolving round the sun in an orbit between the earth and Mars.

The four terrestrial planets—Mercury, Venus, Earth, and Mars—are so called because they do not differ much from the earth in size and density. But beyond the zone of asteroids are the major planets, belonging to a totally different type. They are on an immensely larger scale, but of less density than the inner four; they rotate far more rapidly, and therefore are more flattened at the poles; their visible surface is not solid; and they are accompanied by trains of satellites.

Jupiter is very appropriately named the giant planet. Its mean diameter is 87,000 miles, or about 11 times that of the earth; hence its bulk is 11^3 or 1300 times that of the earth, or $1\frac{1}{2}$ times that of all the other planets put together. Its mass is more than double that of all the rest of the planets, or 310 times that of the earth. But if Jupiter were as dense as the earth, its mass would be 1300 times that of the latter; we therefore conclude that its mean density is only one-fourth of our globe's, and this indicates that very little, if any, of the giant planet is in the solid condition. Observers of Jupiter are at once struck by the very marked flattening at the ends of its axis. Indeed, while the polar compression of the earth is $\frac{1}{294}$, that of Jupiter is $\frac{1}{17}$, from which we infer that the axial motion is very rapid. Observations of markings show that it rotates faster than any other planet, namely, in 9 hours 55 minutes. It takes 11·86 years to go round the sun at an average distance of 483 million miles from it, in an orbit inclined less than $1\frac{1}{2}°$ to the plane of the ecliptic.

The Telescopic Features of Jupiter.—In a telescope of even moderate power, Jupiter is a beautiful and interesting object. It is crossed by sometimes as many as thirty bright and dusky belts of various colours and widths, continually changing their form, but always parallel to the equator. As a rule, there is a very narrow dusky stripe running along the

region of the planet's equator. On each side of this are the brightest zones of the planet, each about 12° wide, and beyond them in each hemisphere is a belt about 20° in width, and of a reddish tint. In higher latitudes are more belts, getting narrower towards the poles owing to the foreshortening due to the curvature of the planet. The belts are doubtless just rifts in the cloudy surface of the planet owing to the tremendous

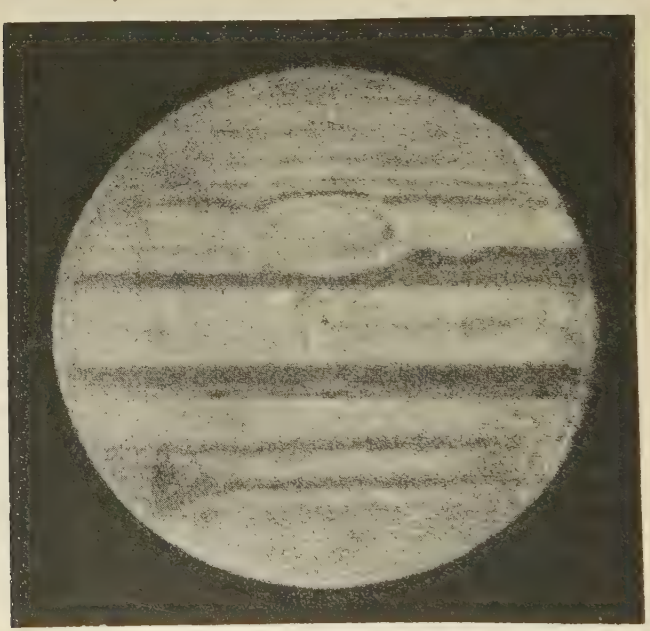


FIG. 175.—Appearance of Jupiter in the great Lick telescope. Drawn by the late Professor Keeler, October 3, 1890. (From *Concise Knowledge Astronomy*. Hutchinson & Co.)

rate of rotation, for places on Jupiter's equator are carried round seventeen times faster than places on the earth's equator. Powerful telescopes show that the main features we have described are overlaid with a variety of spots and streaks, showing lovely colour effects in white, black, vermilion, pink, purple, drab, and brown. In the tropical belts the markings, as a rule, give evidence of great disturbance, whereas in the two broad dusky zones they are more permanent. Just beyond the southern dusky zone (that is, on the boundary of the

tropical and temperate regions) is the famous *great red spot* (see Fig. 175). It is oval in outline, its greatest length being fully one-third and its width fully one-twelfth of the diameter of Jupiter, and its area therefore greater than that of our whole earth. It may have been forming for a long time, but it was not definitely recognized till 1878, and was then of a pale pink colour. After that, its colour deepened to a strong brick-red, and did not change for two or three years. It has since faded several times to the verge of extinction, and then temporarily revived. It is at present (1901) almost invisible, but may again reappear. A strange fact about it is that since its discovery its period of going round the planet has lengthened by five seconds. It cannot, therefore, be a mark on the solid surface of Jupiter, if there is anything solid about the planet. No satisfactory explanation of the great red spot has yet been given.

Atmosphere of Jupiter, and Physical Condition of the Planet.—That Jupiter has a very dense and extensive atmosphere is proved by such facts as the following :—

(1) Spectroscopic examination of its light shows that the rays of the sun are unable to penetrate the atmosphere to any extent, and are for the most part reflected from its upper surface.

(2) Ceaseless changes in the belts and spots show that they are merely markings in a dense envelope of clouds.

(3) Observations of the markings prove that different portions of the planet's visible surface rotate in different periods.

Such considerations show that the atmosphere must be at least thousands of miles deep, if indeed the planet is not gaseous throughout. At any rate, considering its small mean density, it cannot yet have solidified to any great extent. Moreover, the rapidity of the changes taking place in its markings indicates the expenditure of a great amount of heat-energy, and this cannot be derived from the sun, for Jupiter, because of its distance, only gets about one-twentieth of the solar heat that the earth does. The heat must therefore come from the planet itself, which is probably at a temperature not much below incandescence.

The Satellites of Jupiter are five in number. The fifth is nearest to the planet, and was only discovered in 1892 by Professor Barnard at Lick Observatory ; whereas, the four large ones can easily be seen with an opera-glass, and were discovered by Galileo in 1610 with the first telescope ever made. The smallest of these four (No. II.) is almost exactly the size of our moon, while the largest (No. III.) is larger than Mercury.

The nearest of the four satellites (No. I.) revolves round Jupiter in $42\frac{1}{2}$ hours, at about the same average distance from it that our moon is from the earth. Satellite IV. is $4\frac{1}{2}$ times more remote, and requires 16 days $16\frac{1}{2}$ hours to go round the planet. All four revolve in the plane of Jupiter's equator, and, as this very nearly lies in the plane of the ecliptic, they are eclipsed by Jupiter at every revolution, and we have seen how these eclipses were utilized by Roemer to determine the velocity of light.

Observations seem to indicate that (like Mercury and Venus) the satellites of Jupiter have their periods of rotation the same as those of their revolution.

The system of four satellites was so symmetrical and complete that great surprise was caused by the discovery of the fifth satellite in 1892. It is an exceedingly difficult object to see, as it is only like a star of the thirteenth magnitude, and is so close to the planet as to be generally lost in its glare. It can only be seen with the most powerful telescopes at its greatest elongations. Its mean distance from Jupiter's centre is 112,160 miles, and it revolves round it in 11 h. 57 m. 23 s., or only two hours longer than Jupiter's period of rotation. The following are the principal data of the satellites of Jupiter :—

THE SATELLITES OF JUPITER.

Number.	Distance from Jupiter.	Period of revolution.			Diameter.
	miles	d.	h.	m.	miles
V. . . .	112,000	0	11	$57\frac{1}{2}$	100 (?)
I. . . .	261,000	1	18	$27\frac{1}{2}$	2500
II. . . .	415,000	3	13	13	2100
III. . . .	664,000	7	3	$42\frac{1}{2}$	3600
IV. . . .	1,167,020	16	16	32	3000

Saturn, nearly twice as far from the sun as Jupiter, was until 1781 supposed to mark the limit of our solar system. Its mean distance from the sun is 886 million miles, but it varies 50 million miles on either side of this on account of the eccentricity of its orbit. It traverses its immense path in $29\frac{1}{2}$ years, so that its seasons are this number of times longer than ours, and also, so far as the sun's influence is concerned, more accentuated, for its equator is inclined nearly 27° to its orbit. But at its distance the potency of the sun is only $\frac{1}{91}$ of what it is on the earth, and, as in the case of Jupiter, its heat is derived almost totally from itself, for its temperature is still little below incandescence. It is more flattened at the poles than any other planet, its polar compression being one-tenth, and therefore its polar diameter is 7000 miles shorter than its

equatorial, while its mean diameter is 72,000 miles, or a little more than nine times that of the earth. Its volume is therefore 9^3 or 729 times that of the earth, but its mass is ninety-three times the earth's, and hence its mean density is only one-eighth that of our globe. It is thus composed of matter as light as cork, and is by far the least dense of all the planets. Gravity at its surface is only $1\frac{1}{5}$ times that on the earth. As in the case of Jupiter, the period of rotation of parts of its surface differs slightly, but its mean period is only 10 hours 14 minutes.

Telescopic Appearance of Saturn.—To the naked eye Saturn appears a large dull star, but in a telescope it is seen to be traversed by belts parallel to its equator, but much less conspicuous than those of Jupiter, owing chiefly to its inferior brightness. A bright yellowish zone containing indistinct

FIG. 176.—Saturn and his rings. E represents the earth on the same scale.

white spots extends some distance on each side of the equator. In the region of the two tropics there are dusky belts of a greyish or greenish colour, while the poles are covered by extensive caps of a dark greenish hue. Saturn is surrounded by a dense atmosphere resembling that of Jupiter in every respect. We have thus every evidence that Saturn is similar in constitution to the giant planet, but is probably in a still earlier stage of planetary evolution.

Saturn's Rings, their Size, Phases, and Constitution.—The most wonderful telescopic feature of Saturn,

however, is a series of thin, flat, circular rings (see Fig. 176), which surround the planet's equator, the nearest one at a distance of 9500 miles from it. There is nothing like them anywhere else in the solar system. They are three in number, two of them bright, while the third, the one nearest the planet, is called the "*dusky*" or "*crape ring*," being semi-transparent and so faint as to be discernible only through a powerful telescope, and was not, indeed, discovered until 1851. They are generally designated by the letters A, B, and C, A being the exterior one. Between the middle ring, which is the brightest of all, and the outermost is a gap of 1500 miles known, after its discoverer, as *Cassini's division*. In Fig. 176 there is also shown a narrow division running round the middle of ring A, and called *Encke's division*.

The thickness of the rings varies slightly at different parts, but on an average is only about 100 miles. The other dimensions of the rings are as follows:—

Radius of Saturn	36,000 miles		
,, inner edge of C . .	45,500 ,,	}	width of C, 9500 miles
,, outer ,, C . .	55,000 ,,		
,, inner ,, B . .	55,000 ,,	}	width of B, 17,000 miles
,, outer ,, B . .	72,000 ,,		
Width of Cassini's division . .	1,500 ,,		
Radius of inner edge of A . .	73,500 ,,	}	width of A, 10,000 miles.
,, outer ,, A . .	83,500 ,,		

The rings, we have said, are in the same plane as Saturn's equator, which is inclined to its orbit nearly 27°, and therefore

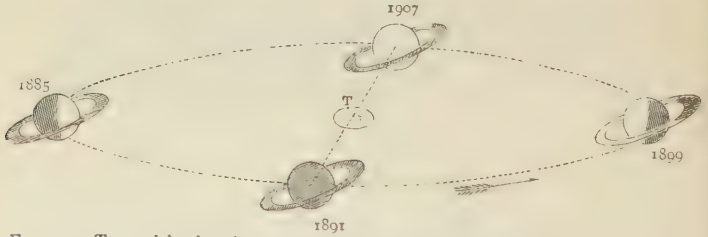


FIG. 177.—To explain the phases of Saturn's rings. *S* represents the sun, the small ellipse the earth's orbit, and the large ellipse the orbit of Saturn. Saturn's rings are inclined 29° to the plane of the earth's orbit. (From Ball's *Elements of Astronomy*.)

to the ecliptic nearly 29°. Hence, as the planet is for about 15 years (half its period of revolution of 29½ years) north of the ecliptic, and then the same length of time south of it, the rings will present different phases to us (see Figs. 177, 178).

When Saturn, in his journey round the sun, is farthest north of the ecliptic, we see the southern side of the rings widely opened out (*e.g.* in the year 1885). About $7\frac{1}{2}$ years afterwards (a quarter of the period of the planet) Saturn crosses the plane of the ecliptic, and the rings are presented to us edgewise, and can be seen only with a good telescope as a fine hair-line (*e.g.* in 1891). For the next 15 years the planet is south of the plane of the ecliptic, and we see the northern side

FIG. 178.—The phases of Saturn's rings. 1, when the planet is farthest north of the plane of the ecliptic; 2, at its descending node; 3, when farthest south of the ecliptic; 4, at its ascending node.

of the rings. During half of this period they gradually open out till they appear at their widest (*e.g.* in 1899), and then gradually close up again till they appear once more like a line (*e.g.* in 1907), which can only be discerned in powerful instruments.

Sometimes the earth and sun are for a time on opposite sides of the rings (*i.e.* the plane of the rings passes between the earth and sun), and then the rings are totally invisible to us, as their unilluminated side is towards us.

If we compare the small thickness of the rings with their enormous diameters, we see that they are too flimsy to consist of solid material strong enough to bear the strain of the planet's gravitative attraction. Nor can they be liquid, for their inner and outer edges move at different rates, and therefore eddies would be produced which would soon break them up. It can be proved mathematically, and from spectroscopic examination of their light, that they consist of an infinite number of separate particles, each revolving like a satellite in its own orbit in the plane of the planet's equator, and obeying Kepler's laws. The two outer rings are brightest, because in them the constituent members are closest together, and therefore reflect most sunlight, whereas in the crape ring the particles are much more thinly strewn, and reflect, therefore, much less light.

Satellites of Saturn.—Saturn is very rich in attendants, for not only has he those wonderful rings, but also nine distinct satellites are now known. The largest *Titan* (No. VI.),

is larger than our moon, being 2720 miles in diameter, and revolves round its primary in nearly 16 days at a distance of 771,000 miles from its centre. Until recently *Japetus* (No. VIII.) was supposed to be the most distant, circulating round Saturn at a distance of 2,225,000 miles in $79\frac{1}{3}$ days; but in March, 1899, Professor W. H. Pickering discovered by photography a ninth satellite, which appears to be three times more remote, and takes about 17 months to complete its orbit. It can only be seen with the most powerful instruments, for its magnitude is only 15·5. Its discoverer suggests that No. IX. should be named after *Phœbe*, a sister of Saturn. It is the smallest satellite of Saturn, for it measures only 200 miles from side to side.

We give here for reference the principal data for these satellites—

THE SATELLITES OF SATURN.

Number.	Name.	Distance from Saturn.	Period of revolution.			Diameter.
		miles.	d.	h.	m.	miles.
I.	Mimas	117,000	0	22	37	750
II.	Enceladus	157,000	1	8	53	800
III.	Tethys	186,000	1	21	18	1100
IV.	Dione	238,000	2	17	41	1200
V.	Rhea	332,000	4	12	25	1500
VI.	Titan	771,000	15	22	41	2720
VII.	Hyperion	934,000	21	6	39	500
VIII.	Japetus	2,225,000	79	7	54	2000
IX.	Phœbe	7,500,000	490?	0	0	200?

Uranus, discovered by Sir William Herschel in 1781, is 1780 million miles from the sun, or fully 19 times the earth's distance. It can therefore receive from the central luminary only $\frac{1}{370}$ the heat and light that the earth does. It pursues its path at a leisurely pace of $4\frac{1}{5}$ miles a second, describing the entire round in 84 years. Its diameter is 32,000 miles, or fully 4 times that of the earth's; its volume is therefore more than 4^3 or 64 times the earth's, although its mass is only about 15 times that of our globe.

Telescopic Appearance.—So remote is Uranus that very few observers have been able to detect any markings whatever on his sea-green disc. Some have seen very faint dusky belts resembling those on Jupiter, and others a white patch from

observation of which the rotation period seems to be about 10 hours. Whether this is a correct estimate is not definitely known, nor is the inclination of its equator to its orbit. The outline of the planet is, however, decidedly elliptical, and from the position of the bulging it is maintained by some observers that the planet's equator is nearly at right angles to the plane of its orbit.

This view is strengthened by the fact that the paths of the moons of Uranus also make this angle with the orbit, and satellites nearly always revolve in the equatorial plane of their primary. Other observers, however, conclude, from the direction of the very indistinct belts that have been seen, that the plane of the equator is inclined from 15° to 40° to the orbits of the satellites. Whichever of these views may turn out to be the correct one, it is at any rate agreed by all that the equator of Uranus is inclined at a considerable angle to the plane of its orbit, and therefore the seasons of the planet would be abnormal were it not that the distance of the sun is so great as to make the vicissitudes of the seasons scarcely perceptible.

Atmosphere.—From the low mean density of the planet it is believed that it has a dense and extensive atmosphere, and that the planet is still to a large extent self-luminous. Its spectrum, for example, is not merely that of reflected sunlight, but contains strong absorption bands towards the red end, and it is this absorption of red rays by the dense atmosphere that causes the green colour of the planet.

Satellites.—Uranus is attended by four moons, whose names in order of distance from the primary are Ariel, Umbriel, Titania, and Oberon. The two inner ones are only about 500 miles in diameter, and are so faint as to be discernible only in great telescopes. The outer ones are about twice as large, and much brighter. The orbits are inclined about 80° to the planet's orbit, and their motion is retrograde, or from east to west, and their periods of revolution range from $2\frac{1}{2}$ days for Ariel to $13\frac{1}{2}$ days for Oberon.

Discovery of Neptune.—Early in the present century it was noticed that Uranus was diverging somewhat from his calculated orbit. The cause of this deviation could not for a long time be explained, and then it began to be suspected that it was due to the disturbing influence of an undiscovered planet beyond Uranus, and two young mathematicians, Adams in England in 1843 and Leverrier in France in 1845, set themselves independently to calculate, from the difference between

the theoretic and actual path of Uranus, the position of the unknown planet. Adams finished his calculations first, and submitted them to the Astronomer Royal, Sir George Airy. After some delay they were sent to Professor Challis at Cambridge to search for the planet in the region indicated, and still further delay took place owing to the necessity of making a careful chart of all the stars in that part of the sky. Meanwhile Leverrier had come to practically the same result, and sent his calculations to Berlin Observatory, where it so happened that a map of that part of the heavens had recently been made, and by comparing it with the sky the new planet was at once discovered by Dr. Galle on September 23, 1846, close to the place indicated by Leverrier. The achievement was considered a great triumph of mathematical astronomy, and a complete proof of the doctrine of the law of gravitation in the solar system on which the calculations were based.

The Surface, Atmosphere, and Satellite of Neptune. —The mean radius of Neptune's path is nearly 30 times that of the earth's, and hence the heat and light of the sun are reduced to $\frac{1}{900}$ of their terrestrial amount. His orbit is only very slightly eccentric, makes an angle of about $1\frac{3}{4}^\circ$ with the ecliptic, and is slowly traversed by the planet in 165 years. The diameter of Neptune (34,500 miles) is more than 4 times the earth's, hence its globe is 72 times as bulky as the earth, although only 17 times as massive, and therefore nearly one-fourth as dense.

Neptune, being fainter than a star of the eighth magnitude, is invisible to the naked eye, but with a good telescope shows a greenish disc, on which no markings can be discerned, and consequently its period of rotation is unknown. The spectrum of the planet seems to be exactly the same as that of Uranus, and therefore it may be inferred that the atmospheres of the two planets are similar.

Neptune's satellite is about the size of our own moon. Its distance from the planet is 224,000 miles; its orbit is inclined 35° to the ecliptic, and is traversed by the satellite in a retrograde direction in 5 days 21 hours.

Uranus and Neptune are thus companion globes nearly alike in bulk, and density, with identical spectra, and therefore probably of the same chemical and physical constitution. In both systems the motion of the moons is retrograde.

Questions.

1. What is known about the physical features and period of rotation of Mercury?
2. Give an account of the results of recent observations in connection with the rotation of Venus and Mercury.
3. Describe and explain the phases of Venus.
4. Tell briefly what is known of the physical features of Venus, and write down its diameter, period of rotation and of revolution.
5. What is the best time to observe Mars, and why? Explain why at some oppositions of Mars the planet is better situated for observation than at others.
6. Give an account of the recent observations which have been made on the physical features of Mars.
7. Describe the surface markings of Mars, and state the causes to which they have been attributed.
8. Describe the telescopic appearance of the surface of Mars, and tell what you know about its satellites.
9. Write a short account of the minor planets.
10. Tell what you know about Eros and the mode of its discovery.
11. Describe the planet Jupiter.
12. What is the cause of the seasons? Contrast the seasons of Mars and Jupiter.
13. Describe the planet Saturn. State the number of its moons and the nature of the rings.
14. Describe the telescopic appearance of the planet Saturn, and state the number of its satellites. Why does this planet appear at times only as a bright disc?
15. In what respects does Saturn resemble Jupiter, and in what respects does it differ from it.
16. Give a brief account of the discovery of Neptune.

CHAPTER XXI.

THE MOON.

The Moon.—The size, distance, and movements of our satellite were described in the *Elementary Physiography*, p. 249, *et seq.* It was there shown that the diameter of the moon is 2163 miles, or $\frac{3}{11}$ that of the earth; hence its volume is $(\frac{3}{11})^3$, or almost $\frac{1}{49}$ of the volume of the earth. But we have also found (p. 277) that the moon's mass is $\frac{1}{81}$ of the mass of the earth, hence the density of the moon is $\frac{49}{81}$ of the density of the earth. Remembering that the attraction of gravity varies directly as the mass of the attracting body, and inversely as the square of the distance, it can be shown, as on p. 275, that at the moon's surface gravity possesses only one-sixth of its power here.

Observation of the Moon's Motion.—We have already learned in the elementary book that the moon has an eastward movement among the stars, and returns to the same position among them in $27\frac{1}{3}$ days; that the moon passes faster to the east than the sun, and gains a whole revolution upon it in $29\frac{1}{2}$ days, which is the interval between two successive new moons or full moons.

The reader should, however, observe this motion for himself. As soon as the new moon can be seen in the western sky, its position among the stars should be noted, and a chart made of the brighter stars near a line drawn eastwards from the moon and at right angles to a line joining the horns of the crescent (as in Fig. 179). Then on each succeeding night when the moon can be seen, its position among these stars should be drawn, and also its phase. The student will thus gain at first hand a very great deal of valuable information. He will learn the cycle of phases of the moon, and the position of its orbit in the heavens; that the moon rises about 50 minutes later each succeeding night; that it moves 13° eastwards among the stars per day; that it returns to the same position among them in

$27\frac{1}{3}$ days, and shows the same phase after $29\frac{1}{2}$ days; that the same markings on the moon are always seen in the same position, and therefore the moon always presents the same side to the earth, or turns once round on her axis while going once round the earth. If the moon's right ascension and declination

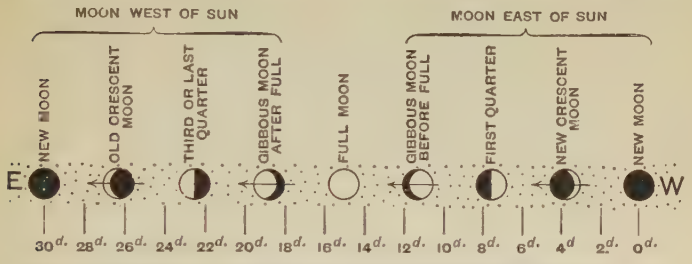


FIG. 179.—Observation of the phases of the moon and its eastward motion among the stars from day to day. (After D. P. Todd.)

be measured accurately each day with a transit circle, and the corresponding positions marked on a star chart, it is found that the moon's orbit is inclined 5° 9′ to the plane of the ecliptic.

Shape of the Moon's Orbit round the Earth.—In the *Elementary Physiography*, p. 275, it is explained how the earth's yearly path round the sun is proved to be an ellipse by the variation throughout the year of the sun's apparent diameter. In like manner, by measuring the moon's angular diameter in different parts of its monthly orbit we find that the latter is an ellipse with the earth in one focus. The moon's apparent diameter varies from 29′ 22″ when it is at apogee to 33′ 32″ when at perigee a fortnight later. This is a greater variation than the sun's apparent diameter undergoes, therefore the moon's orbit is more elongated than the earth's; indeed, the eccentricity of the moon's orbit is found to be $\frac{1}{20}$, whereas that of the earth's orbit is only $\frac{1}{60}$. As to the size of the orbit, the moon's distance varies from 221,600 miles to 253,000 miles, and its average distance is 238,400 miles.

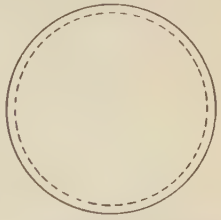


FIG. 180.—Variation in the apparent diameter of the moon in perigee and apogee (dotted circle).

True Form of the Moon's Path in Space—always

concave towards the Sun.—While the moon is moving in this small ellipse relatively to the earth, it also moves around the sun in company with the earth. But the moon's orbital motion is relatively slow—only $\frac{1}{30}$ that of the earth round the sun; also its distance from the earth is very small compared with that of the earth from the sun—only about $\frac{1}{400}$ part—and consequently the moon merely winds slightly in and out along the earth's orbit 12½ times in a year (Fig. 181).

Fig. 181.—Moon's path in space always concave to the sun, even at new moon. In the diagram the divergence is magnified.

Expt. 40.—The earth's distance from the sun is about 92 million miles, and the moon's from the earth about 240,000 miles, and using a scale of ½ inch to a million miles, these distances would respectively be 46 inches and ⅛ inch. Therefore we can represent the true shape of the lunar path during a month by taking a radius of 46 inches (a pencil tied to the end of a string could be used) and drawing an arc of a circle about 24 inches long (this is $\frac{1}{12}$ part of the whole circumference) to represent a portion of the earth's orbit described in a month. Let dots 1, 2, 3, 4, 5 (Fig. 181) at equal distances represent the positions of the earth at the end of each week. Round each dot describe a circle with a radius of ⅛ inch to represent the orbit of the moon round the earth. Mark dot *a* to represent the position of the moon when full, and *b*, *c*, *d*, and *e* its position at the end of each week till the next full moon. Join these positions by a dotted line, and this will represent the moon's path in space during the month. Observe that it is always concave towards the sun at the centre, the concavity slightly increasing at full moon and diminishing at new moon.

The Moon rises and sets on an Average about Fifty Minutes later each Day.—The moon's eastward motion among the stars is about 13° per day. But our time is regulated by the sun, and it too moves eastward among the stars nearly 1° per day. Therefore each day the moon moves 12° (more correctly 12° 11′·4) eastward relatively to the sun. Suppose the moon rises at eight o'clock one night; by the next night it will have moved 12° 11′·4 eastward, and the earth will have to rotate from west to east once and this amount extra to bring the moon again on the eastern horizon. But the earth rotates 360°

in 24 hours; in what time will it rotate the extra bit $12^\circ\ 11'{\cdot}4$?

$$360^\circ : 12^\circ\ 11''{\cdot}4 :: 24 \text{ hours} : x = \text{about } 50 \text{ minutes.}$$

Hence the moon will rise about 50 minutes past 8 the next night, and another 50 minutes later the following one, and so on. This interval, however, varies somewhat, because the moon's eastward motion varies owing to its orbit being an ellipse, and the sun's apparent eastward motion also varies because of the elliptical form of the earth's orbit.

The Moon's Sidereal and Synodic Period.—The moon takes $27\frac{1}{3}$ days (27 d. 7 h. 43 m.) to go exactly once round the earth. This is called the *sidereal period* of the moon, because it is the time it takes to travel from a given star eastwards round to the same star again. But the interval between new moon and new moon is $29\frac{1}{2}$ days (29 d. 12 h. 44 m.), and this is called the moon's *synodic period*, or a *lunar month* or *lunation*. The reason why there is a difference of more than two days between these periods is that during the time the moon takes to revolve once round the earth (about a month) the earth moves over $\frac{1}{12}$ of its orbit, and the moon has to traverse another $\frac{1}{12}$ of its orbit in order to come into the same position relatively to the earth and sun, and to do so takes the two extra days.

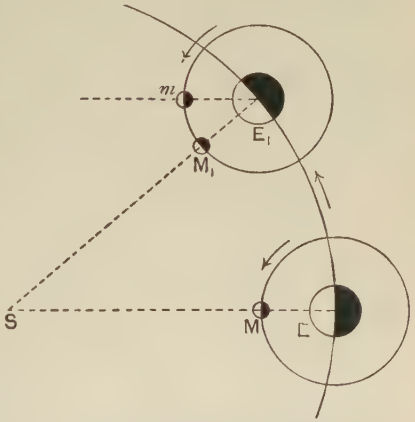


FIG. 182.—To show that the synodic month is longer than the sidereal month.

Fig. 182 will make this plain. Let S, E, and M represent the sun, earth, and moon at new moon, and let the large curve represent a part of the earth's orbit round the sun, and the small circle the moon's orbit round the earth. In a day the earth travels eastwards $\frac{360^\circ}{365}$, therefore in a sidereal month it travels from E to E_1, $\frac{360^\circ \times 27\frac{1}{3}}{365}$, and in the same time the moon

will be at m, once round the earth relatively to the stars. But to return to new moon again it will still have to revolve the extra arc $m\mathrm{M}_1$, which is $\frac{360^\circ \times 27\frac{1}{3}}{365}$, and the time necessary for this can be got from the proportion sum (since the moon travels 360° in $27\frac{1}{3}$ days)—

$$360^\circ : \frac{360^\circ \times 27\frac{1}{3}}{365} :: 27\tfrac{1}{3} \text{ days} : x = \text{about 2 d. 5 h. 1 m.}$$

Hence the synodic exceeds the sidereal month by this amount.

Librations.—The hemisphere of the moon turned away from the earth does not remain wholly invisible to us. There are small periodical oscillations called *librations* that bring portions of it into view.

1. *Libration in Latitude.*—The moon's equator is inclined 6° 39′ to the ecliptic. Hence once a month the north end of the axis is inclined this amount towards the earth, and we see round 6° 39′ beyond the north pole; a fortnight later the south end of the axis is tilted towards us, and we see the same distance beyond the moon's south pole.

2. *Libration in Longitude.*—Although the moon rotates uniformly, its rate of revolution varies, being greatest when the moon is in perigee, and least when in apogee. Fig. 183 will show the effect of this. When the moon is in perigee, at P, a part a on its surface will be towards the earth E. Halfway in time between perigee and apogee the moon will have rotated one-fourth, so that a is at a'; but it will have traversed more than one-fourth of its orbit, so that we on the earth E will see a little distance round its right-hand or western edge. Similarly when the moon is at M′ between apogee and perigee, we see a little round its left-hand or eastern edge.

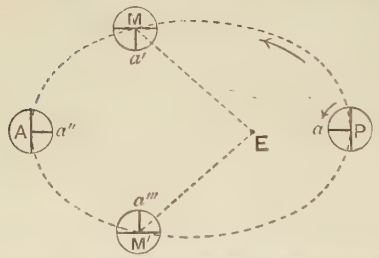


Fig. 183.—To show why we see a little distance round the moon's western edge between perigee and apogee, and a little round its eastern between apogee and perigee.

3. *Diurnal Libration.*—Owing to the earth's diurnal rotation, we are carried alternately 4000 miles to the right and left of a line joining the centres of the earth and moon. When we are on the right or west of this line we see a little distance round the moon's western edge, and when on the left or east of it we see more of the eastern edge. In fact, when the moon is rising in the east its western limb is towards us and we see round it, and when setting in the west we see similarly round its eastern limb.

Owing to the three librations we see 59 per cent. instead of 50 per cent. of the moon's surface, the other 41 per cent. remaining for ever concealed from us.

Telescopic Appearance of the Moon's Surface.—Our greatest modern telescopes, with a magnifying power of 2500, bring the moon virtually within a range of about 100 miles. Also excellent photographs, on a very large scale, of parts of the lunar surface are now taken at various observatories, and thus, with an exposure of a second or two, pictures are taken that it would require months to draw accurately, and by studying these photographs with a magnifying glass, we discover minute features that cannot be seen with any telescope. We have now, therefore, accurate atlases of the moon on a very large scale, and all the principal features of its surface have been classified and named :—

1. *The seas* are the irregular dark patches seen with the naked eye. They were so named because by the early telescopic observers they were believed to be oceans, and the brighter portions continents. Thus we have the Sea of Clouds (*Mare Nubium*), Sea of Serenity (*M. Serenitatis*), Sea of Showers (*M. Imbrium*), etc. We now know that they cannot be seas, for their surface is almost as rugged as other regions of the disc. They are great plains which appear dusky simply because they consist of material of a smaller reflecting power than the surrounding portions of the moon's surface. They may be the beds of primeval oceans which have dried up and disappeared ages ago.

2. *The Craters and Walled Plains.*—The surface of the moon is pitted all over with cones and craters (Fig. 185). Nearly 33,000 have been counted on the visible hemisphere, hence we may safely say that there are not less than 60,000 craters on the entire surface of our satellite. Some of the smaller ones range from half a mile to 10 miles in diameter, but many are 50 or 60 or even over 100 miles in diameter.

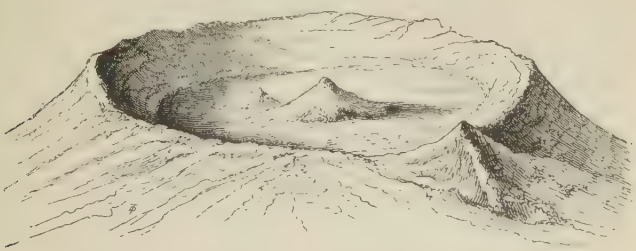


FIG. 184.—A typical lunar crater. (From Ball's *Elements of Astronomy.*)

A lunar crater (Fig. 184) generally consists of a nearly circular ring rising to a height of from 1000 to 20,000 feet (determined by the length of shadow). From the enclosed plain there generally rise several conical peaks of about the same height as the encircling rampart. Copernicus, to the north-east of the centre of the moon's disc (Figs. 185 and 187), is a typical example of a lunar crater. The walls of this crater are about fifty miles in diameter and

13,000 feet high, and a cluster of conical peaks tower 11,300 feet above the central depressed plain from which they rise, or 2600 feet above the general level of the moon's surface. The moon must at one time have been the

FIG. 185.— Photograph of the moon, taken at Paris by MM. Loewy and Puiseux on September 19, 1894. (Inverted as seen in a telescope.)

scene of great volcanic action, and the force of gravity on the moon being only one-sixth of its amount here, the materials were ejected to a great distance, and there accumulated, forming the ring. When the volcanic

energy was nearly spent, the materials fell around the vents and formed the cones.

There are also walled plains from 40 to 150 miles in diameter, with comparatively low walls and interiors generally level, or broken only by slight elevations and depressions. One of these, Archimedes, is shown in Fig. 185. It has a diameter of 50 miles, and walls 600 feet in height. These low-walled plains may not have been formed in the same way as ordinary craters, and are probably the solidified remains of molten lakes.

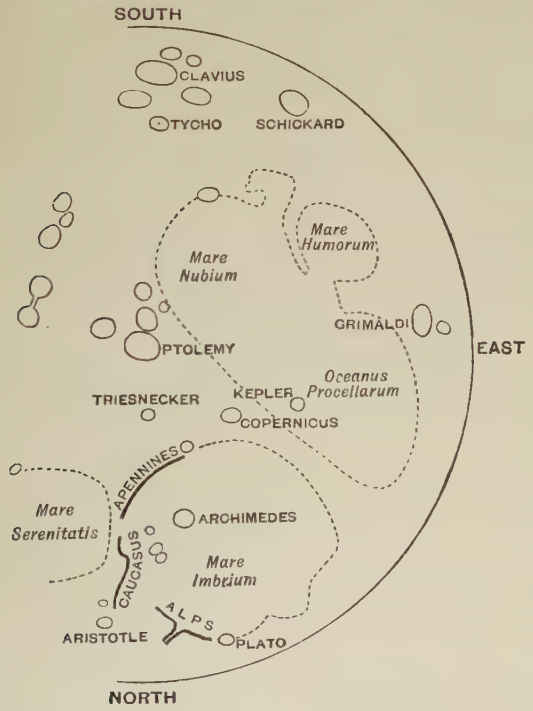


FIG. 186.—Key to the principal features in the foregoing photograph.

3. *The Mountain Chains.*—The mountains on the moon are generally irregularly distributed, and seldom form ranges as on the earth. There are only about ten lunar mountain chains, such as, for example, the Apennines, the Caucasus, and the Alps, seen in Fig. 185. The first-mentioned range is about 500 miles long, and contains mountains 20,000 feet high. The highest peaks on the moon rise to about 36,000 feet.

4. *The rills or clefts* are deep, narrow, and of course waterless, valleys, sometimes 150 to 300 miles long, a mile or more wide, and about a quarter of a mile deep. More than a thousand have been mapped or photographed,

some curved and branching, others running nearly straight through mountain and plain. Some are shown in Fig. 187. Little is known about

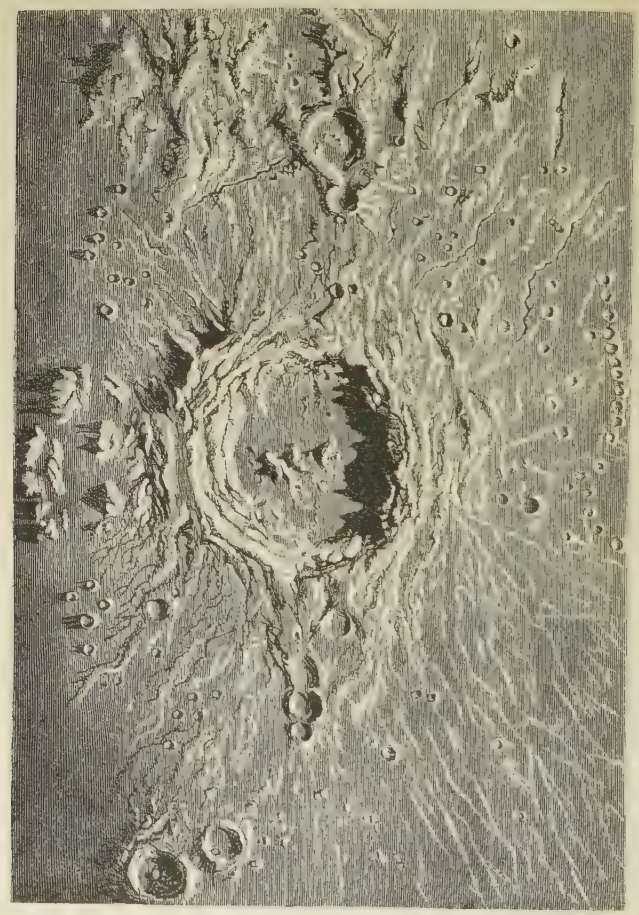


FIG. 187.—The crater Copernicus and its surroundings. (Highly magnified.) (From Proctor's *Moon*.)

their origin, but possibly they are fissures in the surface due to its contraction on cooling.

5. *The rays* are bright streaks, seen best at full moon, radiating in straight lines from several craters, such as Tycho and Copernicus (see Fig. 185).

They extend sometimes for hundreds of miles straight across crater, mountain, and valley. Their width is usually from 5 to 10 miles, and as they cast no shadows they are neither elevations nor depressions. Their nature is as yet inexplicable. They must be of later origin than the formations they intersect, and may possibly be fissures filled up from below with light-coloured material like the trap-dykes on the earth.

The Moon has no Atmosphere.—That the moon is to all intents and purposes an airless globe is proved by the following considerations:—

1. No haze nor clouds can be discerned on it, and hence there is no water on its surface.
2. Lunar landscapes exhibit abrupt transitions from glaring sunlight to shadows of absolute blackness. There is no softening owing to diffusion of light by an atmosphere.
3. During a solar eclipse the outline of the moon's disc against the sun is always perfectly sharp.
4. When the moon passes over a star (or occults it, as it is called) the disappearance of the star is instantaneous, and not gradual as it would be if there were an atmosphere.
5. There is no modification of any kind in the spectrum of a star when it is near the moon's edge. Also, the spectrum of the moon is identical with that of sunlight; there are no extra dark lines owing to the reflected sunlight having to pass through a lunar atmosphere.

If the moon is of the same origin as the earth, she must, in some early period of her history, have had an atmosphere, although probably not an extensive one, and it may have been absorbed by the rocks of the moon as they were slowly cooling down from incandescence.

The Moon's Light and Heat.—We are apt to overestimate the amount of light we receive from the full moon. It is only about $\frac{1}{600000}$ of that of the sun, and if the whole of the visible heavens were covered with full moons they would only give about one-eighth of the light of the sun.

For fourteen days every part of the lunar surface is exposed to the heat of the sun without an intervening atmosphere to temper his rays, but the absence of an air-blanket allows this heat to be radiated into space again almost as soon as it is absorbed. There is now reason to believe that even the moon's surface vertically under the sun never rises to zero Centigrade, and at the end of the fortnight of darkness the temperature approaches that of interplanetary space—probably more than 200° below zero.

The moon is thus a ruined world, devoid of an atmosphere, and therefore of life. Even the volcanoes are now extinct,

and, although our satellite has undergone terrible paroxysms in the past, repose now reigns undisturbed.

Questions.

1. How may the phases and monthly motion of the moon be observed?
2. Distinguish the moon's true and apparent path in the heavens.
3. Show that the moon's orbit is always concave to the sun.
4. Why does the moon rise 50 minutes later each day?
5. Why is the sidereal month shorter than the synodic? How many times does the moon turn on its axis in a year?
6. Explain (and illustrate by diagrams) how it is that we see more than half of the moon's surface; and define the terms "node," "phase," "libration."
7. Explain the following terms: "asteroid," "libration," "lunation," "parallax," "planet's elongation," "right ascension," "synodical period."
8. Describe some of the telescopic features of the moon.
9. What are the facts which lead us to suppose that the moon has no atmosphere?
10. What do we know about the atmospheres of the moon, Mars, and Jupiter? State the methods employed to detect the existence of such atmospheres.

CHAPTER XXII.

COMETS AND METEORS.

The General Appearance of Comets.—A comet has usually three parts—

1. *The coma*, or nebulous, faintly luminous haze, more or less spherical in outline. This is seen in every comet, and, in fact, it is from this essential part that the name "comet," signifying "hairy star," is derived (Gr. *kome*, "hair").

2. *The nucleus* is the bright star-like point near the centre of the coma, and forming with it the *head* of the comet. It is present in the majority, but not in all comets, and in great ones it may shine like a star of the first magnitude.

3. *The tail* is the delicate luminous appendage stretching away into space in the opposite direction from the sun. It varies greatly in length and shape in different comets. Sometimes it is entirely wanting, and, although usually single, it is sometimes multiple, comets having been seen with no fewer than six tails.

Dimensions of Comets.

1. *Dimensions of the Coma.*—Probably all comets whose heads are less than 15,000 miles in diameter are too small to be seen by us. The heads of telescopic comets vary from about 25,000 to more than 100,000 miles in diameter. The head of a great comet that appeared in 1811 was 1,200,000 miles across, and this is the greatest on record.

2. *The nucleus* has a diameter ranging from 8000 miles to a mere point of light only 100 miles across.

3. *The tail* is seldom less than 10,000,000 miles long, and in several cases longer than 100,000,000 miles—that is, greater than the distance between the earth and sun. The tail is roughly conical in shape, and at its outer extremity may measure millions of miles from side to side.

4. *The Mass and Density.*—We determine the mass of heavenly bodies by their gravitational effect on other bodies

near them. This test cannot, however, be applied to comets, for, although they have repeatedly come near the earth and other planets, the motion of the planets has not been disturbed in the slightest degree. There is no doubt the mass of a comet is tons, but whether hundreds, or thousands, or millions of tons we cannot tell. All that we definitely know about a comet's mass is that it is quite insignificant compared with that of the earth.

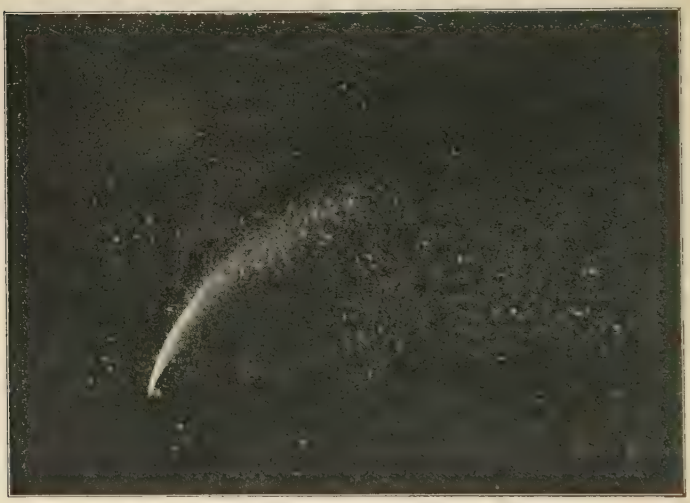


FIG. 188.—Donati's triple-tailed comet, October 5, 1858.

But we have seen that the volume of comets is enormous, and hence, since their mass is so small, they must be bodies of extraordinary tenuity. This is shown, too, by the fact that even very faint stars can be seen through the head or tail of a comet with hardly any perceptible loss of lustre. The substance in a comet must, therefore, be many hundred times less dense than any vacuum we can produce by our air-pumps. We must not, however, conclude from their extremely small density that comets consist only of tenuous gas, for we shall see that there is good reason to believe that the nucleus, at any rate, consists of widely separated small solid bodies surrounded with vapours.

Changes in the Appearance of a Comet as it approaches and recedes from the Sun.—When a comet

is first seen in the telescope approaching the sun from the depths of space, it appears like a roundish hazy patch that can hardly be distinguished from a globular nebula. At this stage its light is very feeble, and it moves very slowly, owing to its great distance from the sun. As it approaches nearer the sun, the nucleus appears near the front part of the nebulosity, which is now more elliptic in shape (Fig. 189). As the comet approaches still nearer, its velocity increases, and it gives out more light, and a number of gauzy envelopes, one outside the other, and diversified by jets of luminous material, appear to surround the nucleus on the sunward side. As the approach continues, the material thus ejected towards the sun is at a certain stage repelled backwards, and forms the tail directed away from the sun (Fig. 190). This action continues to increase for several days after the comet has passed its perihelion point, at which stage the tail often shoots out at the rate of several million miles a day. Then as the comet recedes from the sun, the same phases are passed through in the reverse order, and, when last seen, the comet once more resembles the faint patch of nebulosity from which it grew.

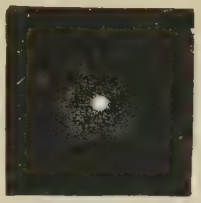


FIG. 189.—Donati's comet on July 2, 1858, showing the coma and nucleus.

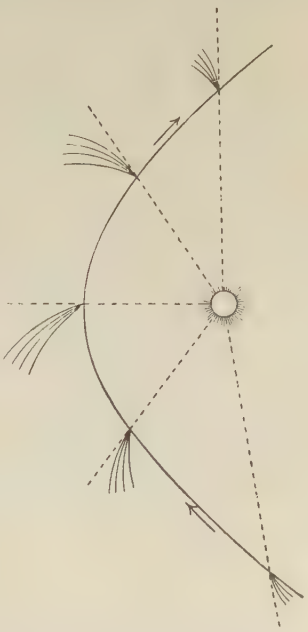


FIG. 190.—The tail of a comet is always directed away from the sun.

It may be mentioned that the analysis of a comet's light shows that it too undergoes changes according to distance from the sun. But first we should state that laboratory experiments prove that when a gas is raised to a moderate temperature its spectrum consists of bright bands, and as the same substance is raised to a higher temperature the spectrum becomes one of bright lines. Now, the spectrum of a comet at a considerable distance from the sun consists of bright bands due to carbon, but as the temperature

rises with approach to perihelion, this gives place to bright lines due to sodium, manganese, iron, and other substances; and as the comet recedes the same changes are passed through in the inverse order.

The Development and Types of Cometary Tails. – We cannot as yet say with certainty how the tails are formed. If the head of a comet consists, as there is good reason to believe, of a swarm of meteoritic particles, then the increased attraction produced by approach to the sun will cause great tidal disturbances in the swarm. The heat produced by the increased number of collisions will partially vaporize the particles. The vapours formed must, of course, be attracted by the sun; but this gravitational attraction is overcome by some repelling force, and the gases are driven off to form the tail. What the exact nature of the latter force is we are not absolutely certain, but as the chief repulsive force in nature is electricity, and the sun is a great storehouse of all forms of radiant energy, it is generally believed that the repulsion producing the tail is due to the electrical action of the sun on the comet. The force of electrical repulsion is proportional to the surface of the body acted on, whereas the attraction of gravity is proportional to the mass, and as the highly rarefied materials composing the tail have an immense surface, but very small mass, the sun's electrical repulsion is greater than its gravitational attraction, and they are therefore repelled backward.

Professor Bredichin, a Russian astronomer, from a comparison of all available drawings and descriptions of comets, finds that the tails may be divided into three types—

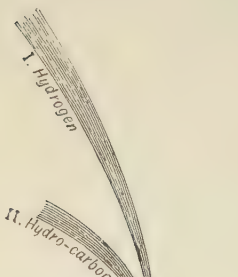


Fig. 191.—Three types of cometary tails (Bredichin).

1. *Long straight tails.* The tails of the great comets of 1811 and 1861 were of this type.

2. *Gently curved plume-like tails*, like the principal tail of Donati's comet of 1858. This is by far the commonest type of tail.

3. *Short strongly bent tails*, curving sharply round from the nucleus, as in Encke's comet.

Bredichin calculates that in tails of the first type the sun's repulsive action is about fourteen times as great as its gravitational attraction, and hence the matter is repelled with a velocity far too great to be deflected much. In tails of the second type, the force of repulsion is about $1\frac{1}{2}$ or

2 times as great as solar gravity; while the short stubby tails are caused by the sun's repulsive force being about one-fifth of his gravitational attraction. These relations between the repellent and attractive energies depend upon the density of the material acted upon, and hence he believes tails of type 1 consist chiefly of hydrogen, type 2 of hydrocarbons, and type 3 of vapours of iron with admixtures of sodium and other substances, which, because of their density, are more subject to the action of gravity. Subsequent observations seem to verify these conclusions.

FIG. 192.—Photograph of Swift's comet. (By Professor Barnard, April 6, 1892. Exposure 65 minutes.)

FIG. 193.—Photograph of same comet on the succeeding night. (Exposure 50 minutes.)

During recent years photography has with great success been applied to the study of comets, and it seems likely to revolutionize our present opinions as to the development and types of cometary tails. It reveals to us changes in these appendages of a rapidity and vastness hitherto undreamt of.

Indeed, the appearance of a tail one night may bear little resemblance to what it was the previous night (compare Figs. 192 and 193), and of all this the eye takes no cognizance. Moreover, the visual and photographic appearances of a comet are very different. The tails, instead of having the symmetrical and homogeneous structure represented in drawings, are perceived on the sensitive plate to consist of innumerable filaments sometimes forming bundles, and they may be straight, curved, crooked, interlacing, or knotted, or the tail may seem broken into fragments. We cannot as yet explain these rapid changes, but they point to an irregular evolution of energy causing the matter to be driven away from the nucleus in a spasmodic manner, rather than to vaporization due to a steady rise of temperature with approach to the sun.

Motion of Comets.—When a comet is observed night by night, it is found to have usually a rapid motion relatively to the stars, and as soon as a new comet is discovered, astronomers endeavour to ascertain its orbit by accurately measuring its position on several nights.

1. *Forms of Cometary Orbits.*—In every case the orbit is found to be either an *ellipse*, or *parabola*, or *hyperbola*. We have already explained (p. 314) what is meant by the eccentricity of an orbit, and we may now add that when the eccentricity is zero the orbit is a circle, when the eccentricity is less than unity it is an ellipse, when it is unity the orbit is a parabola, and when greater than unity it is an hyperbola. Comets which move round the sun in ellipses are called *periodic comets*, because they regularly return after a longer or shorter period to the neighbourhood of the sun. Comets moving in parabolic paths approach the sun and recede from it in directions practically parallel to the major axis of the orbit, whereas those moving in hyperbolic orbits have their direction of approach and recession widely divergent. It will also be seen from Fig. 194 that parabolas and hyperbolas are open, not closed, curves, so that comets moving in them come once into the sun's neighbourhood, and, after doing obeisance to him, disappear into the unmeasured depths of space never to return.

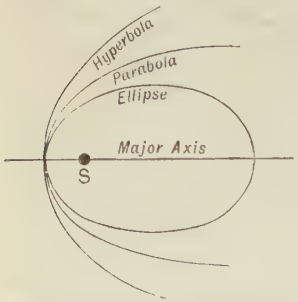


Fig. 114. Forms of cometary orbits. The sun is always in a focus of the orbit, whether it is elliptic, parabolic, or hyperbolic.

The number of distinct comets on record is between 800 and 900, and of these more than 270 have had their orbits

computed. In a few cases there is still doubt as to the form of the orbit, for when an ellipse is very eccentric it can hardly, near perihelion, be distinguished from a parabola. The great majority—fully 200 of the 270—move in parabolic paths, 6 or 7 have hyperbolic orbits, and about 50 move in ellipses in periods varying from three and a half to thousands of years, and at least 17 of these periodic comets have been already observed at more than one return.

2. *Inclination of Orbits to Ecliptic.*—Unlike planets, comets do not keep near to the ecliptic, but move in paths making all angles with it, from 0° to 90°. The orbits of periodic comets are, as a rule, but little inclined to the ecliptic; but for other comets the inclination is on an average about 50°.

3. *Direction of Motion in Orbit.*—The six comets moving in hyperbolic orbits have a *direct* or west to east motion. The same is true of the great majority of periodic comets. The parabolic comets have no decided preponderance either way, but a slight majority move in a *retrograde* or east to west direction.

From what has been said, we see that the orbits of comets differ from those of planets in having a much higher eccentricity, in being inclined at all possible angles to the ecliptic, and that the motion in some cases is direct and in others retrograde.

Groups of Comets.—Amongst the other vagaries of comets must be mentioned the curious circumstance that in several instances comets that could not possibly be identical have been found following in each other's wake in one and the same orbit. The most remarkable group of this sort consists of the great comets of 1668, 1843, 1880, and 1882.

There are about half a dozen such groups of comets, and probably in each case they represent fragments of a large comet disrupted by the great tidal disturbance produced by very near approach to the sun.

Relation of Periodic Comets to Planets.—When periodic comets are tabulated according to their aphelion distance from the sun, it is found that in many cases they pass outwards to the neighbourhood of the orbit of one or other of the exterior planets. Thus each of these planets has its own cometary family. All the comets, for example, whose periods are less than 8 years are related in this way to Jupiter, the 33-year comets to Uranus, and the 75-year comets to Neptune. Jupiter's family of comets numbers fully two dozen, Saturn's 9, Uranus's 8, and Neptune's 5 (including Halley's comet, see Fig. 162).

There is little doubt that comets originally describe open

orbits, either parabolas or hyperbolas; but as they journey to the sun they may pass near one of the major planets, and have their velocity so much reduced by it that they will thenceforth travel round the sun in elliptical orbits extending outwards to the planet by whose overpowering attraction they have been added to the solar system.

Some Noteworthy Comets.—Few comets appear which are visible to the naked eye, but on an average about half a dozen telescopic comets are seen every year.

1. **Halley's Comet.**—This comet is remarkable as being the first comet whose periodicity was discovered. When it appeared in 1682, Halley, the astronomer royal at the time, computed its path, and found it to be an ellipse which the comet should describe in 75 or 76 years. This view was strengthened by the fact that it resembled in appearance and orbit comets recorded in 1607 and 1531. He predicted, therefore, that it would return about 1758, and as he could not himself witness the verification of his prophecy, he wrote, "wherefore if it should return according to our prediction about the year 1758, impartial posterity will not refuse to recognize that it was first discovered by an Englishman." As the time approached its return was eagerly watched for, and it was first seen on Christmas Day, 1758, and was in perihelion in March, 1759. Since then it has gone by the name of Halley's Comet. It returned punctually in 1835, and is next due in 1910.

2. **Encke's Comet** is small and inconspicuous, but it is famous because of the shortness of its period of revolution round the sun—only $3\frac{1}{3}$ years, as was first proved by the German astronomer whose name it bears. A curious, and as yet inexplicable, circumstance about it is that at each revolution its period shortens by about $2\frac{1}{2}$ hours. Also it fluctuates considerably in form and brightness at successive apparitions. In 1898 it was just at the limit of visibility to the naked eye. Its next return is in 1901.

3. **The Lost Biela's Comet.**—The second comet of short period discovered was by an Austrian officer, named Biela, in 1826. He computed its orbit and found the period to be $6\frac{1}{2}$ years. At its reappearance in 1846 it was seen to have split into two unequal parts, pursuing the same path, and each provided with a tail and bright nucleus. When next seen, in 1852, the distance between them had increased to more than a million miles. Since then they have never been seen, and probably never will. It was due, for example, in November, 1872, and although the comet was not seen there was a brilliant shower of meteors, and the same was repeated in 1885 and 1892. The meteors are now known as the Bielids (also sometimes called the Andromedes, because the paths of the meteors, if prolonged backwards, appear to radiate from a point in the constellation of Andromeda), and it is now generally believed that they are the products of the disintegration of the lost comet. The history of this body furnishes important evidence of the meteoric nature of comets, and points to the fate that must eventually befall every periodic comet.

4. **Donati's Comet.**—This beautiful comet attained its greatest brilliancy in October, 1858. Its principal tail was sharply curved, about 40° long, and at its extremity was 8° wide. It had also two very long, narrow, and nearly straight tails (Fig. 188). The comet will not again be visible for 2000 years. Its motion is retrograde along a path which is an exceedingly

elongated ellipse, with its aphelion point 5½ times more distant from the sun than Neptune is.

Meteors or Shooting Stars, Meteorites.—Many millions of little solid bodies called meteors, each moving in its own orbit round the sun, enter our atmosphere every day. Most of the particles are probably no larger than a pea, but so rapidly are they moving that they possess great kinetic energy. This energy of motion is, by the collision with our atmosphere and the friction in passing quickly through it, transformed into heat, and as the white-hot particles rush silently through the air they leave behind them a train of glowing gas. After travelling on an average about sixty miles they are completely vaporized; in rare cases, however, they fall to the earth's surface, and are then called *meteorites*.

Showers of Meteors, Radiant Points.—Meteors are much more plentiful at some seasons than others; for example, showers of them occur in April, August, and November. If we carefully watched one of these showers, and put down on a star-chart the directions of as many as possible of the luminous trails, it would be found that, on producing them backward, they would all seem to *radiate* from a small area of the sky called the *radiant point*, or simply the *radiant*, of the shower (Fig. 195). Just as the parallel rails on a railroad or furrows in a ploughed field seem to diverge from a point in the distance, so the divergence of the luminous paths is due to perspective, and is a proof that the meteors in the shower are moving through space in parallel lines, the radiant point being simply the vanishing point. According to Mr. Denning, of Bristol, an authority on the subject, there are about 3000 distinct radiants known. The showers are named after the constellation in which their radiant falls. Thus we have the Andromedes, the Leonids, and the Perseids, with their radiants in the constellations of Andromeda, Leo, and Perseus respectively.

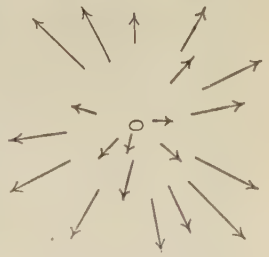


FIG. 195.—To illustrate the radiant point. The arrows represent the directions and lengths of the luminous paths, and near the radiant point (represented in the diagram by the small oval) they are shorter, as there they are coming nearly "end-on" straight towards the observer, and are therefore much foreshortened by perspective.

Meteoric Orbits.—Since the shower of falling stars corresponding to a particular radiant recurs periodically, the swarm

of meteors must be travelling in an elliptic orbit round the sun. From the position of the radiant point in the heavens, and the appearance of the luminous streaks, we can determine the size and shape of the orbit, how it lies in space, and how long the swarm takes to traverse it. For example, Fig. 196 represents the orbit of the Leonids, and it will be seen that it comes very near to the part of the earth's orbit occupied by our globe about the 14th of November. It is computed that the Leonids take $33\frac{1}{4}$ years to traverse their orbit; hence they can only be in the neighbourhood of the earth every 33 years. For instance, great showers of them were seen between the 12th and 14th of November in the years 1799, 1833, and 1866, and a moderate one in 1899. But the tendency is for a swarm of meteors to gradually spread themselves along the whole of the orbit (perhaps owing to the inner members moving faster because of the sun's greater attraction, and the outer ones slower), and form a continuous ring. In cases in which this has happened, there must be an annual display at the time when the motion of the earth in its orbit brings it into proximity to the orbit of the swarm. This is the case, for instance, with the Perseids, which occur every year about the 10th of August. The April shower is also annual.

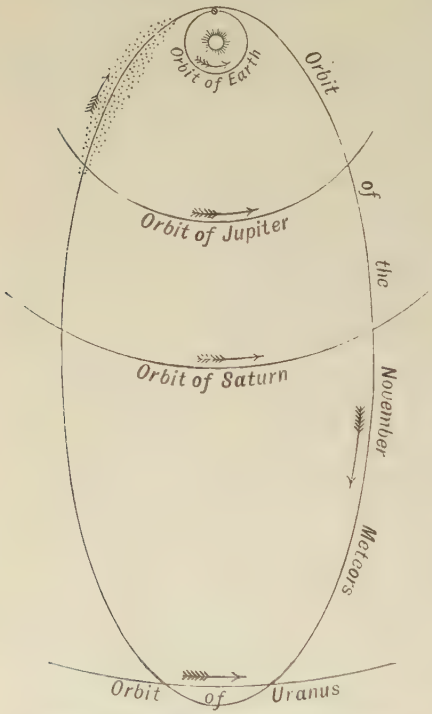


FIG. 196.—Orbit of the November meteors and of Comet I., 1866.

It must not, however, be supposed from Fig. 196 that the

orbit of the Leonids lies in the plane of the earth's orbit (see Fig. 197).

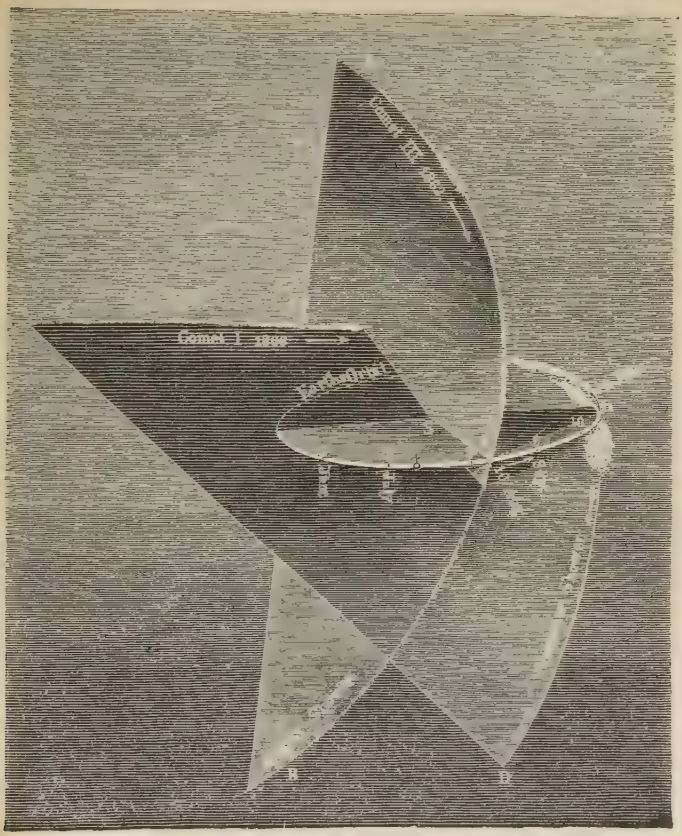


FIG. 197.—Perihelion parts of the orbits of the Leonids and the Perseids. The orbit of the November shower makes an angle of 17° with the ecliptic, and the August shower about 90°.

Nature of Comets.—We have the following evidences of the close connection between comets and meteors :—

1. *Coincidence of orbits of comets and meteoric orbits.* In 1866 Schiaparelli published a paper on the Perseids, in which he pointed out the remarkable fact that they move in the same path as the Comet III., 1862 (see Fig. 197). Shortly after this it was found that the orbits of the Leonid

meteors and Comet I., 1866, are identical, and now there are about seventy or eighty similar coincidences known.

2. *The changes in the spectrum of a comet are similar to those in the spectrum of meteorites with change of temperature.* Sir Norman Lockyer has shown that the sequence of changes in the spectrum of the nucleus of a comet during its revolution round the sun is exactly the same as the changes produced in the spectrum of meteorites vaporized at different temperatures in our laboratories.

Hence it is believed that *comets are just denser swarms of meteors*, the members of the shoal being small bodies, possibly only a fraction of an inch in diameter, and far enough apart even in the nucleus to let starlight pass freely through it. The light of comets consists to a small extent of reflected sunlight, but it is mainly due to light emitted by them partly owing to the incandescence produced by collisions between the meteoric particles, and partly to disruptive electric discharges produced by the sun's action.

Meteor swarms producing periodical star showers are doubtless just the *débris* of former periodic comets. Every return to perihelion has a disintegrating effect upon a comet—hence the meteor swarms sometimes travelling in the same orbit as a comet. When the disintegration is complete the comet becomes "lost," as in the case of Biela's comet and others, and a similar fate must eventually happen to every periodic comet.

QUESTIONS.

1. Describe the general appearance and dimensions of comets.
2. Describe the constituent parts of a comet.
3. State the telescopic and spectroscopic changes observed in comets as they approach perihelion, and the causes which produce them.
4. What is a comet, and what are the changes produced in it during its journey round the sun?
5. What are the views held as to the origin of comets' tails?
6. State the results of recent investigations into the types of cometary tails?
7. Tell what you know about the orbits of comets.
8. What is meant by a periodic comet? Describe the appearance of a comet as the sun is approached.
9. If the earth had no atmosphere, how would the phenomena of shooting stars be affected?
10. How can the distance of a meteor from the observer, and the height from the earth at which it appears and disappears, be determined?
11. State what you know concerning the connection between comets and meteorites.
12. How was the connection between comets and meteor swarms established?
13. What is known regarding the nature and chemical composition of comets?

CHAPTER XXIII.

THE SIDEREAL SYSTEM.

Up to this point we have confined our attention chiefly to our own little planet and the system to which it belongs. Neptune, on the frontier of that system, is thirty times more distant from us than the sun is, but beyond this is the great sidereal system consisting of stars and nebulæ, the nearest of which is 9000 times more remote than Neptune. They form a stellar universe so vast that even the largest telescopes can only partially penetrate its immeasurable depths.

The Constellations.—From the remotest times the stars were imagined to be arranged in groups forming the outlines of certain figures, human and other. These groups are called constellations. The ancients recognized 48 constellations, and named them chiefly after their gods and heroes, or some object which the arrangement of the group was thought to resemble. Their number has been largely added to by different astronomers since then, but only about 60 are now recognized, viz. the 12 zodiacal constellations through which the sun appears to journey in a year, and 27 north of the zodiac, and 21 south of it.

The stars in each constellation are distinguished in order of brightness by the Greek letters, α (alpha) for the brightest star, β (beta) for the next, γ (gamma) for the third, and so on. A few constellations contain more than twenty-four bright stars, and in that case, when the Greek letters are exhausted Roman letters are used, and afterwards numerals. The Greek letter is followed by the genitive of the Latin name of the constellation; thus α Lyræ is the brightest star in the Lyre, δ Orionis is the fourth brightest in Orion, and so on. About one hundred conspicuous stars have special names in addition to their constellation name; thus, α Lyræ is called *Vega*, α Canis Majoris is called *Sirius*, and α Tauri is named *Aldebaran*, etc.

The Magnitudes of Stars.—By the magnitude of a star

is meant its degree of brightness. The ancient astronomers divided stars into grades or magnitudes according to their brightness. Twenty of the brightest stars, half of which are north of the celestial equator, are placed in the first magnitude. Of these Sirius is decidedly the brightest. About sixty-five stars (including the Pole Star) belong to the second magnitude, those fainter still form the third magnitude, and so on, till we reach the sixth magnitude comprising the faintest stars visible to the naked eye on a clear moonless night. Telescopic stars range from the seventh up to the fifteenth, sixteenth, or even seventeenth magnitude in the largest instruments. Decimal fractions are now used to express all gradations of magnitude: thus we may have stars of magnitude 3·4, 2·7, and so on.

In order to measure the brightness of stars it is necessary to adopt a definite scale of magnitudes, and the one now universally used is based on the fact that a star of the first magnitude gives one hundred times as much light as a star of the sixth magnitude. The interval between any two successive magnitudes is therefore the fifth root of one hundred, or 2·5: that is to say, a star of the first magnitude gives—

2·5	times as much light as a star of the	second	magnitude	
$(2·5)^2$	or about 6 times as much, etc.	third	,,	
$(2·5)^3$	,, 16 ,, ,,	fourth	,,	
$(2·5)^4$	,, 40 ,, ,,	fifth	,,	
$(2·5)^5$	,, 100 ,, ,,	sixth	,,	

And so on. Thus a star of any magnitude gives 2·5 times more light than a star of the next fainter magnitude, and 2·5 times less light than one of the next brighter magnitude.

Until quite recently the naked eye was alone employed in estimating star magnitudes. Now several instrumental methods are employed. One of the simplest is afforded by the *wedge-photometer* (Gr. *phos*, *photos*, "light;" *metron*, "a measure"), which consists of a strip of neutral-tinted glass about 6 inches long and tapering from the one end to the other. The wedge is placed with its thin edge behind the eye-piece of the telescope, and is moved along until the light of the star is just extinguished; then by means of a scale the star's magnitude is at once deduced.

Various explanations have been given of the great variety in brightness among stars. The magnitude may sometimes depend upon distance, but this is by no means a universal rule, for many of the fainter stars have been proved to be relatively near the solar system, and several of the brighter ones to be exceedingly remote. The magnitude of stars seems to be more dependent upon their size, and upon the intrinsic brightness of their surfaces due to their differences of temperature and of constitution.

Number of the Stars.—As we look at the heavens on a clear moonless night, we are apt to imagine that the number of

stars visible to the naked eye is countless. As a matter of fact, they can easily be counted, and, surprising as it may seem, the number visible at one time does not exceed two or three thousand. But only half of the sky is seen by us at one time, and, if we include the hemisphere below the horizon, we are safe to assert that the number of stars perceptible to unaided vision in the whole heavens does not exceed five or six thousand.[1] By the use of even an opera-glass this number is increased to about a quarter of a million, and altogether about two millions may be seen through a small telescope. The stars within the range of our largest modern telescopes are

FIG. 198.—Photograph by Professor Barnard of the Milky Way in the constellation of Cepheus. Exposure 7 hours.

estimated at about 125 millions. Photography reveals at least 160 million stars, and, indeed, photographs like Fig. 198 seem to indicate that the sensitive surface would be well-nigh a mass of images of stars if sufficient length of exposure were allowed.[2]

[1] Excluding, of course, the stars in the *Milky Way* or *Galaxy*, that arch of faintly luminous light seen spanning the heavens on a clear night. It is composed of innumerable faint stars not individually discernible without a telescope.

[2] The chief reasons why more stars can be photographed than ever can be

It is worthy of remark that as the brightness of stars decrease their number rapidly increases, and the number in each class of magnitude is about three times that in the next brighter magnitude. The numbers of stars of the successive magnitudes have been estimated as—

First magnitude,		20	Sixth magnitude,		5000
Second	,,	65	Seventh	,,	20,000
Third	,,	200	Eighth	,,	68,000
Fourth	,,	500	Ninth	,,	240,000
Fifth	,,	1400	Tenth	,,	720,000.

Star Catalogues and Charts.—Just as gazetteers contain lists of places on the earth, with their latitude and longitude for determining their position on a map, so catalogues of stars are lists of stars arranged in the order of their right ascension, and giving also the declination and the necessary data for determining the exact position of a star at any particular hour. But we have seen that right ascension and declination steadily alter, so that the values given in the catalogues refer to a specified epoch. Several well-known catalogues have been drawn up either for certain regions of the sky or for stars down to a certain magnitude. Thus we have the British Association Catalogue (abbreviated to B.A.C.), giving the position of 8377 stars; also Lalande's (Ll.) and Argelander's (Arg.), etc., and 4298 B.A.C. or 17,251 Ll. refers to the star of that number in the catalogue specified.

Learning the Constellations.—Familiarity with the chief constellations, their relative positions, and principal stars, is of course the prime essential in the study of the heavens, and one should be so thoroughly acquainted with them as to be able to recognize them at a glance, no matter what their position relatively to the horizon may be. Perhaps one of the easiest methods of learning the positions of the constellations is by means of a planisphere (Philips's is cheap and convenient), which shows the principal stars visible in our latitude at the different hours during every month of the year.

seen with the most powerful telescope are: (*a*) the photographic plate has a greater range of sensibility than the retina of the eye. The eye is only affected by the visual rays in the ether, whereas the chemical plate is sensitive to the infra-red and ultra-violet rays as well as the visual ones; (*b*) the action on the photographic plate is cumulative. Impressions on the retina die out as soon as made, and therefore if we do not see an object at the first glance we shall not do so by continued staring. On the other hand the chemical action on a photographic plate exposed for an hour is 3600 times what it was at the end of a second; hence, however feeble the rays of a star, they must, if allowed to fall upon the same part of the photographic plate for a sufficient length of time, ultimately produce chemical action there, and imprint an image of the star.

The most important of the northern constellations is Ursa Major (that is, *the Great Bear*), also called the Plough and "Charles's Wain" (Figs. 199 and 200). The stars Alpha and Beta of it are called "the Pointers," because a line drawn through them points towards the *Pole Star*. The Pointers are 5° apart, and the Pole Star is about five times this distance from Alpha. The Pole Star is of the second magnitude, and is at the tip of the tail of the *Little Bear* (Ursa Minor). A line drawn from the tail of the Great Bear through the Pole Star to a nearly equal distance on the other side gives the position of *Cassiopeia* (Fig. 199), the five brightest stars of which form the letter W.

FIG. 199.—The principal constellations within 60° of the north celestial pole. By turning the figure it shows how the stars appear on looking north between 8 and 9 p.m. during the month the name of which appears at the top.

If a line were drawn from Gamma to Alpha in the Great Bear and produced, it would pass near a bright yellow star called *Capella* (α Aurigæ) (see Fig. 199). This is the brightest star north of the celestial equator. Again, if the curve formed by the three stars in the tail of the Great Bear be continued backwards, it passes near a very bright orange-coloured star. This is *Arcturus* (α Boötis) (see Fig. 200); four stars of this constellation are shown in Fig. 199, but not Arcturus, as its declination is 15°.

Another very bright star, *Vega* (α Lyræ) (see Fig. 199), may be recognized at the vertex, as it were, of a right-angled triangle of which the line joining the Pole Star and Arcturus is the hypotenuse. The three, Capella, Arcturus, and Vega, are nearly of the same magnitude, and are the brightest stars in the northern hemisphere.

If a line were drawn from the Pole Star to Capella, and produced fully as far again, it would direct us to the constellation of *Orion*, that splendid collection of stars which forms so prominent a feature of our winter sky. The four conspicuous stars in it form a quadrilateral (Fig. 201), the two upper

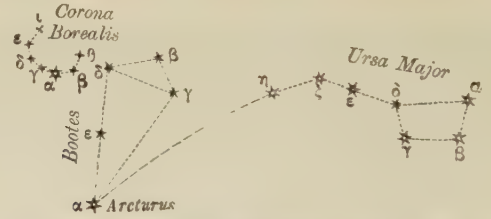


FIG. 200.—The brightest stars in the constellations of the Great Bear, the Bear-keeper (Bootes), and the Northern Crown (Corona Borealis.) (From Ball's *Elements of Astronomy.*)

ones representing the shoulders, and the two lower ones the feet of the giant. The upper one to the left is *Betelgeuse* (α Orionis), and the lower one to the right is *Rigel* (β Orionis). The three stars in line near the centre of the quadrilateral were supposed to represent the belt of the giant (Orion's Belt), and they point south-eastwards to Sirius, the brightest star in the firmament, and in the other direction to Aldebaran (α Tauri), a very bright star in the Bull—the constellation that contains the well-known cluster, the Pleiades, which when once recognized can never be mistaken.

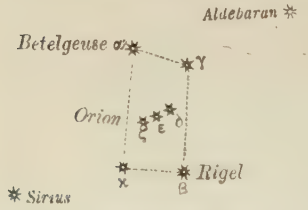


FIG. 201.—The brightest stars in the constellation of Orion and its neighbourhood. (From Ball's *Elements of Astronomy.*)

The positions of these being known, it is easy to find other constellations and stars by means of charts.

Photographic Charts of the Entire Heavens.—On the proposal of Sir David Gill, Astronomer Royal at the Cape of Good Hope, an international congress of astronomers met at Paris in 1887 and resolved to photograph the entire heavens. The work was begun in 1891, and is now nearly completed. Eighteen observatories scattered over the world (of which two are in this country, viz. Greenwich and Oxford University observatories), are taking part in the work. Each observatory has a certain part of the sky allotted to it, and all are using similar telescopes, viz. refractors of 13-inch aperture and

11 feet focal length (see Fig. 202), and plates of exactly the same size—four square degrees. About 44,000 plates altogether will be required.

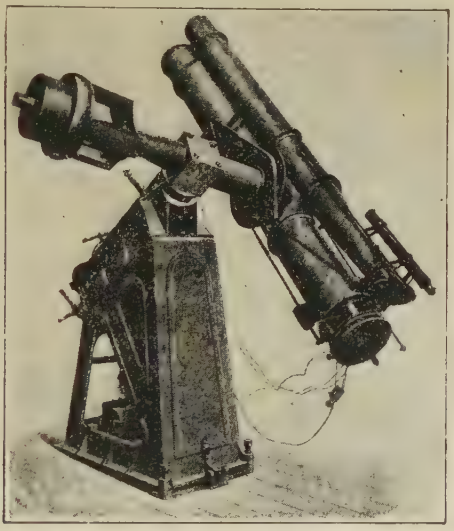


FIG. 202.—The standard form of equatorial telescope made by Sir Howard Grubb for the International Photographic Chart of the sky. The small telescope is the "finder," for quickly picking up any celestial body required; the middle one is the guiding telescope, to ensure that the instrument is exactly following the heavens during the exposure; and the lowermost large telescope is the photographic one, with the plate-holder at its nearer end. (From *Good Words*.)

The programme includes—(1) The drawing up of a *Star Catalogue* based on photographic plates exposed for six minutes (see Fig. 203). In this way about two million stars down to the eleventh magnitude will have their right ascension, declination, magnitude, etc., catalogued. (2) A *Photographic Chart of the Heavens* from plates exposed for forty minutes. The chart will contain all stars to the fourteenth magnitude inclusive—probably more than 50 millions in all. This magnificent picture of the entire heavens will, when finished, cover a globe 22 feet in diameter, so that in two or three generations astronomers, by comparing the chart with their own observations, will know much more than we do about the direction and velocity of the motion of the solar system in space, movements amongst the stars, and changes of nebulæ, etc.

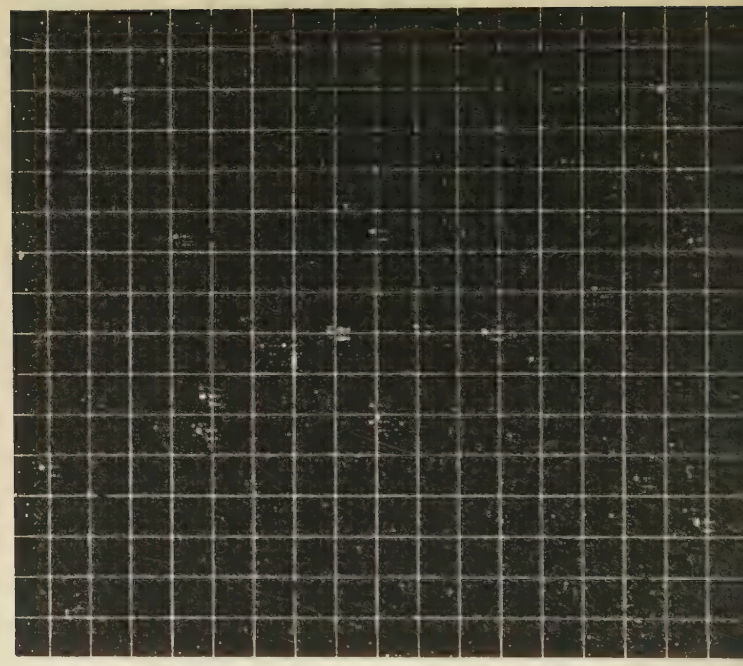


FIG. 203.—A photograph taken for the International Star Catalogue. (Exposure 6 minutes.) Observe the faint network of lines (5 millimetres apart) previously photographed on the plate for the more accurate determination of the positions of the stars.

Motions of the Stars. Before the invention of the telescope and the other means of accurately measuring the relative positions of the stars, they were supposed to occupy absolutely fixed places in the heavens, and hence they were termed the "fixed stars," to distinguish them from the planets and other bodies always shifting their positions in the sky. We now know that, far from the stars being "fixed," they are in ceaseless motion in the firmament. Their movement may be considered by us under two heads: (1) motion athwart the line of vision, causing an alteration in the relative positions of the stars; this is generally called the "proper motion" of stars; (2) motion of direct approach or recession in the line of sight, and this of course produces no alteration in the relative positions of the stars, nor of their apparent positions in the heavens. Fig. 204

may help to make these points plain. If O be the position of an observer on the earth, and if a star move across the line of sight from A to B, then its position on the celestial sphere will change from *a* to *b*; this is its proper motion. If a star move from C to D, or *vice versâ*, in the line of sight, its position *c* in the heavens will not alter. More commonly the motion of stars is a combination of these two, partly across and partly in the line of sight, as from E to F, and the former component will cause the star's position in the heavens to alter from *e* to *f*.

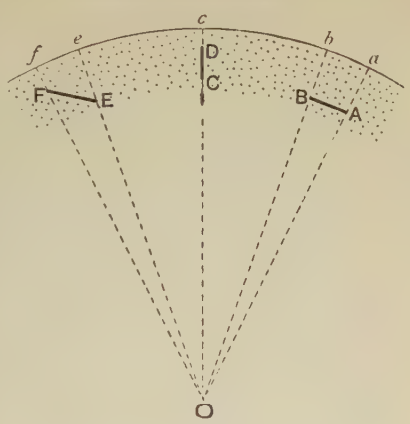


FIG. 204.—To illustrate the motions of stars.

The "Proper Motion" of Stars, or Motion of Stars across the Line of Sight.—If by means of the transit circle the declination and right ascension of stars be measured and corrections made for aberration, annual parallax, refraction, precession, and nutation, it is found that, in the case of many stars, these two co-ordinates show a progressive change due to the motion of the stars at right angles to the direction in which the star is seen. In the table on p. 268, we have given the annual amount of the proper motion for a few stars. The three stars with the greatest proper motion per annum, so far as yet discovered, are—

	"
1830 Groombridge	7·6
9352 Lacaille	6·9
61 Cygni	5·2

and the proper motion of even 1830 Groombridge is so small that it takes nearly three centuries for the displacement to amount to as much as the moon's angular diameter. If we know also the star's distance, we can tell the rate in miles per second corresponding to this angular motion across the line of vision, and for the three stars mentioned this is calculated to be respectively 232, 71, and 30 miles per second. Because of

the rapidity of its motion, No. 1830 in Groombridge's catalogue has been called "the runaway star," but it has recently been found that even its velocity in miles is exceeded by two other stars, namely, μ Cassiopeiæ and Arcturus, which are believed to have the extraordinary proper motions of 305 and 375 miles per second respectively.

As a result of the proper motions of stars, the appearance of the constellations in which they occur must, in course of time, change, but the distortion is so gradual that it will require 300 or 400 centuries to be appreciable to the naked eye. For example, in the Great Bear five of the brightest stars are moving in the same direction, and two in the opposite direction as indicated by the arrows in Fig. 205.

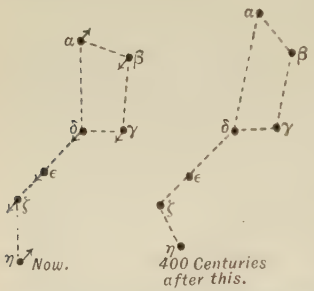
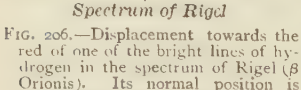


FIG. 205. Slow change in the appearance of Ursa Major, owing to the proper motion of its component stars (according to Proctor).

Stellar motions in the line of sight cannot be detected by micrometric measurements with a transit circle, and they would probably have remained for ever undiscovered but for the invention of the spectroscope. We have already fully explained at pp. 74 and 76 how, in accordance with the general principle discovered by Doppler, if a celestial body is approaching us the lines in its spectrum are slightly displaced towards the violet end of the spectrum, and towards the red end if receding, the rate of approach or recession being determined by the amount of displacement of the lines from their normal position as determined by comparison with the corresponding lines in the spectrum of a substance vaporized in the laboratory. The measurement is an exceedingly delicate one, and the recent application of photography to spectra has greatly increased the accuracy of the results. It is now certain that the following stars, among others, are approaching our system: Arcturus, Vega, 61 Cygni, Pole Star, Procyon; and that Rigel (Fig. 206), Aldebaran, Capella, etc., are receding from it. The Pole Star and Procyon



Spectrum of Rigel

FIG. 206.—Displacement towards the red of one of the bright lines of hydrogen in the spectrum of Rigel (β Orionis). Its normal position is indicated by the thin dark line.

(α Canis Minoris) are approaching us at the rate of 16 and 7 miles per second respectively, and Rigel and Aldebaran are receding from us about 39 and 30 miles a second.

Proper Motion of the Sun.—As we walk along an avenue of trees we observe that the trees we are approaching appear to space out, while those we are leaving behind appear to close up. In like manner, it is found that when the proper motion of thousands of stars in the same region of the sky is examined, they seem to have a common motion outwards from a certain point, while in the opposite region they have a common motion inwards towards a centre. This double phenomenon is due to the sun's motion through space carrying with him his whole family of planets, satellites, and comets. According to the most recent investigations, the point towards which the solar system is moving (called *the apex of the sun's way*) is not far from the bright star Vega, and the point from which it is receding (called the *anti-apex*, or *quit*) is about 15° south of Sirius, the velocity of the motion being probably about 14 miles a second, and so vast is the orbit in which the sun is moving that no curvature of it has yet been detected, although our luminary is doubtless moving round some centre.

The motion of the stars, both across and in the line of sight, is due partly to a real motion of the stars, and partly to this motion of our system.

Variable Stars.—Many of the stars, when carefully observed, are found to fluctuate in brilliancy. These are called "variable stars," or simply "variables." Nearly 1000 of this most interesting class of celestial bodies are now known. The variation is usually regular and periodic, and then *the amount of the variability* of the star is the difference of the extreme magnitudes, and *the period of the variability* is the time that elapses between two successive greatest brightnesses. In the case of some variables, however, the fluctuations of brightness are irregular both in amount and period.

Variable stars may conveniently be classified as follows:—

I. Those with Regular Variability.

(*a*) *Variables of long period*, that is, variables with a period of several months. ο Ceti (Omicron Ceti), also called Mira, is a typical star of this class.

(*b*) *Variables of short period.* β Persei (Beta Persei), also called Algol, is a type of this class.

(*c*) *Variables exhibiting several fluctuations of brightness in each complete period*, as for example, β Lyræ (Beta Lyræ).

II. Those with irregular variability, such as η Argûs (Eta Argûs).

III. Temporary stars, or new stars, are those which blaze out suddenly in the course of a few days or weeks, and then slowly wane till they are lost to view, or nearly so. Such a star is called *Nova* followed by the genitive of the name of the constellation, as Nova Aurigæ, Nova Cygni, etc.

Long-period variables, also called "Omicron Ceti variables," include perhaps one-half of the known variables. The average period of the whole group is about a year. They are usually reddish in tint, and they decrease in brightness at about the same rate as they increase, and hence their light-curves are like steep waves with sharp crests (see uppermost curve in Fig. 207).

The characteristic star of this group, Omicron Ceti, popularly known as Mira, or the Wonderful, varies in magnitude

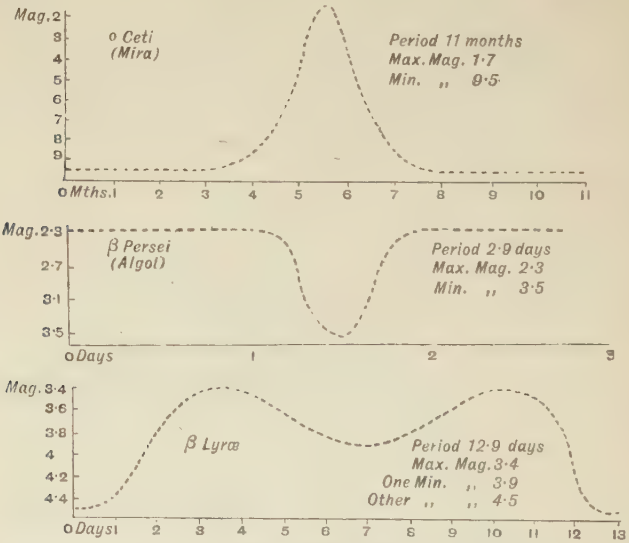


Fig. 207.—The light-curves of typical variable stars with a regular period. Time is measured along the horizontal line in each case, and the magnitude at any time is represented by the length of the perpendicular between the horizontal line and the curve.

from 1·7 to 9·5 in a period of 331 days, or about eleven months. It remains at its faintest magnitude for about eight

months, or two-thirds of its period; then it rapidly increases in brightness, remains at its maximum for ten or twelve days, and afterwards rapidly decreases again. These variations are indicated in the star's light-curve, Fig. 207.

Short-period variables, also called "Algol variables," are about twenty in number, with periods varying in length from $17\frac{1}{4}$ days down to $5\frac{1}{2}$ hours. They remain at their maximum brightness during nearly their whole period; then their light suddenly drops within an hour or two to a minimum, remains at this for a fraction of an hour, and almost as suddenly returns to the maximum.

The light-curve of Algol, or Beta Persei, the typical star of this class, is the middle one in Fig. 207. The period of the star is 2·9 days. It remains at its greatest brightness (magnitude 2·3) for the greater part of the period; then it rapidly diminishes in brilliance for $4\frac{1}{4}$ hours, and remains at a minimum (magnitude 3·5) for only $\frac{1}{4}$ hour, and then increases again in $5\frac{1}{4}$ hours to its normal brightness.

Variables of the Beta Lyræ type are peculiar in that they undergo more than one fluctuation of brightness during their period. For example, β Lyræ (which is visible to the naked eye, being the nearest bright star to the south of Vega), in its short period of 12·9 days, shows two maxima and two minima (see lowest curve in Fig. 207). At its principal maximum its magnitude is 3·4, and the two minima are respectively 3·9 and 4·5.

Irregular Variables are not numerous. Eta Argûs, lying in the midst of the great nebula in Argo, is remarkable for the fluctuations its light has undergone. We have not space to give the particulars of even a small fraction of its vicissitudes. Halley recorded it in 1677 as being of the fourth magnitude; then it rose to the second, sank again to the fourth, then increased in brightness till in 1843 it excelled Sirius; by 1886 it sank to magnitude 7·5, and has since then slightly increased. A period of fifty years has been suggested for it, but it probably has no regular period.

Temporary stars, or new stars, are comparatively rare phenomena. The earliest mention of one is in 134 B.C., and Pliny informs us that it was the sudden appearance of this new star that led Hipparchus to draw up the earliest catalogue of stars ever constructed. From that time until the beginning of this century about eighteen are mentioned in old records. A notable one suddenly appeared in Cassiopeia in November, 1572, and was carefully observed by Tycho Brahé. It

outrivalled even Jupiter in brightness, being for a while visible in broad daylight, and in eighteen months totally disappeared. In 1604 a new star of equal brilliance was observed by Kepler in Ophiuchus, and was visible for about a month longer than its predecessor. Until February, 1901, no new star matched these two in splendour. In 1866 a very remarkable star, sometimes called the "Blaze star," suddenly appeared in Corona Borealis. Till then it had been a tenth magnitude star, but in that year it suddenly flashed up into a star of the second magnitude, and in the course of six weeks returned to its original faintness, and appeared as if nothing had happened to it. In 1876 a new star appeared with equal suddenness in a part of the constellation of the Swan (Cygnus), where no star existed before. It appeared suddenly as a third magnitude star, remained at this for two days, in the course of a month was invisible to the naked eye, and can now only be seen in powerful telescopes as a star of the fifteenth magnitude.

On February 1, 1892, a postcard was sent to Dr. Copeland, the Astronomer Royal for Scotland, announcing the discovery of a new star of the fifth magnitude in Auriga. The discoverer was Dr. T. D. Anderson. It was found, on examining photographs, that the nova had existed for over a year before it was detected. In three years after its discovery it descended to a faint nebulous star of magnitude 10·5. Measurements seem to indicate that this star was as distant as the Milky Way, and hence its remarkable outburst of light must actually have occurred as early as the beginning of the nineteenth century. In order to settle, if possible, the origin and constitution of these mysterious objects, the spectrum of Nova Aurigæ was more carefully examined than that of any previous nova.

Several new stars have appeared since then, and a remarkable one was detected in Perseus on February 22, 1901, by the same keen observer. Its discovery was made about 2.40 a.m., and at that time its magnitude was 2·7, or fully half a magnitude fainter than the Pole Star. When seen next evening Nova Persei was of the first magnitude, and was brighter than Capella or Aldebaran, and thus in the course of a few hours had become the brightest star north of the celestial equator. Nova Persei ranks, indeed, as the brightest new star since that of 1604.

A remarkable feature of this nova was its sudden appearance and its rapid diminution of brightness. Photographs of the region show that on February 19, 1901, it was invisible, or at least fainter than the eleventh magnitude. After February 23rd

its light began rapidly to wane. On February 27th its magnitude was 1·7, on March 1st its magnitude was 2, on the 5th it was 2·7, on the 17th it was 5·5, and this nova thus promises to be an unusually short-lived one.

Causes of Variability.—No general explanation can be given covering all classes of variables.

1. *Variables of the Mira type* are believed by Sir Norman Lockyer to be still in the condition of meteoric swarms, and to be due (Fig. 208) to a larger swarm causing a smaller swarm to

Fig. 208.—Sir Norman Lockyer's meteoritic theory of long-period variables.

revolve round it (or rather round their common centre of gravity, as in the case of the earth and moon). At every return of the smaller swarm to its periastron point (that is, the part of its orbit nearest to the central swarm) vast numbers of the meteoric particles of the two swarms collide and are raised to a state of incandescence. The range of the variability will depend upon the closeness with which the groups approach each other.

2. *Variables of the Algol Type.*—Their period is too short and the changes of luminosity too sudden for the above explanation. But in their case the variability is readily accounted for by the theory of the periodic partial interposition of a dark body between us and the star. The attendant is smaller than the

primary round which it revolves and its orbit is presented nearly edgewise to us, so that at every revolution it partially eclipses the light of the star. Fig. 209 will make this plain; the upper part of the diagram represents the system as we actually see it, and the lower part is the system as it would appear if we could look perpendicularly upon it.

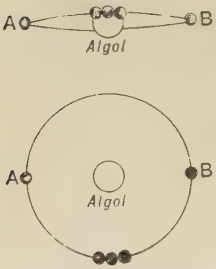


FIG. 209. Orbit of Algol's dark companion shown in section in the upper figure, and in plan in the lower.

This theory has been fully confirmed spectroscopically by Professor Vogel, who has calculated that the diameter of Algol is about 1,070,000 miles, that of its dark companion 84,000 miles, and the distance between their centres $3\frac{1}{4}$ million miles.

3. *Variables of the Beta Lyræ Type.*—The explanation of these is still doubtful, but recent investigations with the spectroscope seem to indicate that β Lyræ is a very close double star, the members of which revolve round each other in periods identical with that of the star's double fluctuation.

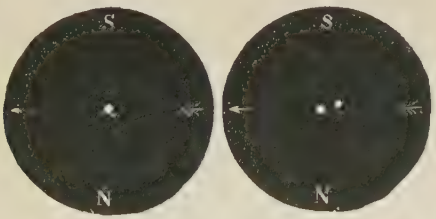
4. *Irregular variables* have not yet been satisfactorily explained. One suggestion is that the variability is due to vast areas of dark spots on the star, similar to spots on the sun, and that the irregular variability is due to the rotation of the star combined with the periodicity of the spots themselves. Lockyer suggests that the irregular variability may be due to "the revolution of more than one swarm or body round another (or their common centre of gravity)."

5. *New Stars.*—Photographs of the spectrum of Nova Aurigæ showed at least eight bright lines displaced towards the red end such an amount that Vogel calculated that the body producing them was receding from us at the enormous rate of 300 miles a second. Also each bright line had a companion dark line or band displaced towards the violet to an extent indicating that the body producing the dark lines was approaching us with a speed of 420 miles a second. Hence this new star was due to the collision of two bodies in space, one approaching and the other receding from our system. Lockyer maintains that the bodies were meteoritic swarms—a sparse swarm receding from us and producing the bright lines in the spectrum, and a dense swarm approaching us and producing the dark lines by selective absorption of its light shining

through the sparse swarm. When the collisions ceased, the incandescent gases produced by them gradually cooled, and the spectrum became identical with that of nebulæ.

All the new stars that have appeared since 1892 have been characterized by spectra almost identical with the one just described. Nova Persei, for example, had a spectrum consisting of numerous bright bands flanked by dark lines on their more refrangible side, thus indicating that the luminosity was due to the collision in space of a dense meteor-swarm with a sparse one, and the displacement of the lines in the spectrum from their normal position showed that the former swarm was rushing through the latter with the extraordinary relative velocity of about 700 miles a second in a direction towards the earth.

Double Stars.—Many of the stars, when examined with a good telescope, are found to be double, multiple, or even made up of a dense cluster of stars. Pairs of stars that appear close to each other in the heavens are catalogued as double stars. About 12,000 such are known, and every year the number is now being rapidly increased by spectroscopic methods. Fig. 210 shows two double stars easily within reach of a small telescope.



61 Cygni. Epsilon Lyræ.

FIG. 210.—Two double stars as seen in a 3-inch telescope.

The Distinction between Optical Doubles, and Physical Doubles or Binaries.—Stars may appear double merely because they are seen in nearly the same direction in space, and although they seem close together, one of them may be at an immense distance behind the other. Such pairs of stars are called *optical doubles*, to distinguish them from *physical doubles* or *binaries*, whose component stars are really near each other and form a system rotating about their common centre of gravity. Only by careful and prolonged observation of the relative positions and

distances apart of the components can we determine to which class a pair belongs. If the components are found by micrometric measurements to revolve in a closed orbit, then they are called a binary star.

Binary Stars.—About two hundred of these are now known, and in more than a fourth of the cases the orbits have actually been calculated. The periods of revolution range from $5\frac{1}{2}$ years to no less than 1500 years.

A very good example of a binary system is *Alpha Centauri*, which is also, so far as we know, the nearest star to us. The components are respectively of the first and second magnitude, and each is of about the same mass as the sun. Their period of revolution is eighty-one years.

In several cases one of the pair in a binary is dark. *Sirius*, familiarly known as the Dog Star, is a binary of this kind, and long before the companion star had been detected, its position and orbit were calculated from the effects of its attraction on its luminous neighbour. When discovered by the late Alvan G. Clark in 1862 as a very faint star, only visible in powerful telescopes, its position closely agreed with that predicted from theory. Its mass is about the same as that of the sun, while Sirius has a mass $2\frac{1}{3}$ times as great as the sun. The Dog Star and its faint companion revolve round their common centre of gravity in fifty-two years.

Binaries discovered by the Spectroscope.—There are binaries so close as to appear single to the highest telescopic power, and whose duplicity has only been revealed by periodical doubling of the lines in their spectrum. It is evident that if two stars revolve round their common centre of gravity in a plane not perpendicular to the line of sight, then when the two are in the same direction as seen from the earth the lines in their spectra will coincide, but at other times they will appear to move in opposite directions relatively to the earth, and the lines of the one approaching us will be moved a little towards the violet end of the spectrum, and the lines of the other towards the red end. This gives us the period of their revolution, and by measuring the amount of the displacement of the lines we learn their orbital velocity, and from these two data we can tell their mass as compared with the sun.

Multiple Stars and Star Clusters.—In many cases there are more than two stars in the same field of view, and thus stars may be *triple*, *quadruple*, etc. All such cases are generally included under the name *multiple stars*. Epsilon Lyræ is a good example. To the naked eye it appears a fourth-magnitude star near Vega; a small telescope divides the star into two components, as shown in Fig. 210; a telescope of

moderate power divides each of the two components into a pair; and a large telescope shows at least three other stars.

If a multiple star has more than seven or eight components, it is generally called a *star cluster*. These aggregations are usually divided into two classes, namely (1) *irregular clusters*, in which the stars are loosely and not very thickly scattered: and (2) *globular clusters*, in which the stars are closely aggregated in a more or less spherical area.

FIG. 211.—The globular cluster Omega Centauri. Reproduced by permission from a photograph by Sir David Gill. Exposure 3 hours 3 minutes.

The Pleiades is one of the most conspicuous star clusters in the heavens, and belongs to the first-mentioned type. With the naked eye six up to ten or even thirteen stars can be seen, according to the keenness of vision. With a moderate telescope

100 stars can be counted, while a photographic plate exposed for $17\frac{1}{2}$ hours contained the images of nearly 7000 stars.

The most remarkable example of a globular star cluster in the northern hemisphere of the heavens is the *Hercules cluster*. To the naked eye it is just visible as a hazy star of the sixth magnitude, but a large telescope shows that it is a group of several thousands of stars. Another truly marvellous object of this class is the cluster *Omega Centauri* (Fig. 211). It is visible in the southern hemisphere as a single star of the fourth magnitude, but in a photograph of it 6400 stars were counted, although the actual number is believed to be considerably greater.

Nebulæ.—Celestial objects that appear like a mass of luminous fog and cannot be resolved into star-clusters are called nebulæ (Lat. *nebula*, "a fog"). Before the days of the spectroscope, a nebula was looked upon simply as a star cluster too distant to be broken up into separate stars by our telescopes. Analysis of their light has, however, shown that they are quite different in constitution from groups of stars, and that their luminosity is mainly due to glowing gas. In all about 8000 nebulæ are now known, but only two are visible to the naked eye, namely, the great nebulæ in Orion and Andromeda. The distribution of nebulæ over the sky is just the opposite of that of stars, for while stars become more and more numerous towards the Milky Way, nebulæ increase in number with angular distance from that bright zone. The physical explanation of this fact is not known.

Classification of Nebulæ.—It is usual to divide nebulæ into five classes according to their appearance and shape —

1. Irregular nebulæ.
2. Annular and elliptical nebulæ.
3. Spiral or whirlpool nebulæ.
4. Planetary nebulæ.
5. Nebulous stars.

1. *Irregular Nebulæ.*—The largest and most irregular of all the nebulæ is that in the constellation of Orion. It is easily seen without a telescope, being the middle one of the three stars forming the sword of Orion, which hangs from the eastern end of his belt. With even a small telescope this star (Theta Orionis) is found to be multiple, consisting of four members forming what is often called the "trapezium." These are completely enveloped in the nebulosity, and hence are not seen in the magnificent photograph of the nebula taken by Dr. Roberts (Fig. 212). Even with small instruments a dark gap can be seen (shown on the right of the main nebulosity in the photograph) leading up towards the trapezium, and as this in telescopes has the appearance of the open mouth of a fish, the nebula has sometimes been called the *fish-mouth nebula*.

FIG. 212.—Photograph of the irregular nebulæ in Orion, by Dr. Roberts. Exposure 3¼ hours. (From Miss A. M. Clerke's *System of the Stars.*)

The light of the nebula is of a greenish-white tinge of unequal intensity in different parts, and fluctuations of brightness in several regions of it have been observed. Wisps of nebulosity extend out in different directions, and involve other stars in the constellation.

Another great irregular nebula surrounds the variable star Eta Argûs, in the southern hemisphere.

2. *Annular or ring nebulæ* are very rare, only a few being known in the whole heavens. The best-known one lies between Beta and Gamma Lyræ, to the south of Vega. The photograph of the nebula (Fig. 213) shows the complexity of its structure better than the greatest telescopes can do. It consists of an oval ring of nebulosity surrounding a very faint nebulous star.

FIG. 213.—Photograph of the ring nebula in the Lyre. Exposure 6 hours. (By permission of M. Trepied.)

Elliptical nebulæ are probably due to perspective, being merely ring nebulæ looked at more or less sidewise, and hence every degree of ellipticity occurs, from ovals down to straight lines. The most remarkable object of this class is the well-known nebula in the constellation of Andromeda, which lies on the other side of Cassiopeia from the Pole Star (see Fig. 199, p. 369). Even the unaided eye can recognize its nebulosity near Eta Andromedæ. Its structure was never clearly revealed until Dr. Roberts took his splendid photograph of it in 1888. Fig. 214 by no means shows all the details of the original plate, but even in this reproduction we can see that the nebula consists of a central elliptical mass surrounded by two or three concentric rings of nebulosity separated from each other by dark intervals. The two small nebulæ seen near it have very probably been formed from it, and indeed the whole appearance of the nebula suggests that it represents a great system in the making.

3. *Spiral or Whirlpool Nebulæ.*—The most conspicuous example occurs in the constellation of the Hunting Dogs (Fig. 215). As seen in great telescopes, it has the appearance of a swirl or spiral, but the photograph of it by Dr. Roberts shows it to consist really of a succession of rings

surrounding a nucleus, the rings being knotted with brighter parts as if the nebulous material is condensing to form stars. In other words, the

FIG. 214.—Photograph of the elliptical nebula in Andromeda. Exposure 4 hours. (By permission of Dr. Roberts.)

so-called spiral nebulæ are merely elliptical ones in a more advanced stage of evolution.

4. *Planetary nebulæ* were so named by Sir William Herschel because of their resemblance to the discs of planets, although, of course, much fainter. They are round, or nearly so, have pretty definite outlines, and are usually of uniform brightness throughout. They are a numerous class of objects, a good example being 97 Messier (so called because it is No. 97 in Messier's catalogue of nebulæ).

5. *Nebulous stars* are stars surrounded by a nebulous haze, and having the appearance in ordinary telescopes of a star out of focus. They are not a numerous class. The star Epsilon Orionis, in the centre of Orion's Belt, is enveloped with a nebulous atmosphere. The principal stars in the Pleiades have been found to be similarly surrounded.

Nature of Nebulæ.—We have seen that the spectrum of the sun consists of a bright band crossed by a great number of fine dark lines caused by absorption of the sun's light as

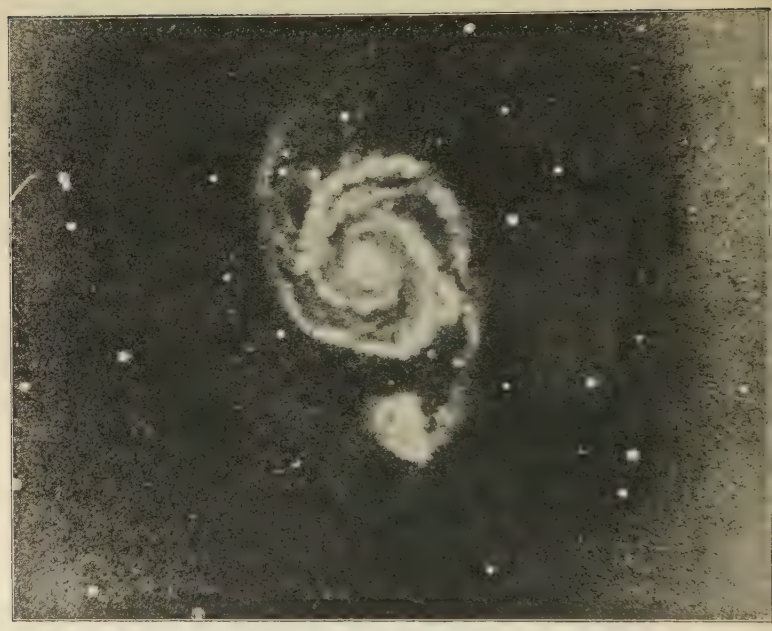


FIG. 215.—Photograph of the spiral nebula in Canes Venatici. Exposure 4 hours. (By permission of Dr. Roberts.)

it passes through his gaseous envelope. The spectra of most of the stars are somewhat similar, showing that they too are suns consisting of an incandescent nucleus surrounded by cooler gases. The spectrum of a nebula, however, is totally different from this, and consists of three or four bright lines, and sometimes as many more faint ones. The application of photography to nebular spectra has revealed many new lines—about forty in all. The lines are chiefly those of hydrogen, helium, and other substances not yet recognized among the terrestrial elements. Hence, since nebulæ give bright-line spectra, they consist (see p. 71) mainly of glowing gases—in large part hydrogen and helium. On this all astronomers are agreed. But Sir Norman Lockyer has brought forward a large amount of spectroscopic evidence, which we need not give here, to show that scattered through the glowing gaseous mass are numerous little solid particles. Indeed, he believes that nebulæ

are sparse swarms of meteoric particles in the celestial spaces, and that the luminous gases producing the light are due to the particles being raised to such a temperature by collisions with each other as to be partially vaporized.

Laplace's nebular hypothesis of the origin of systems is that they first of all exist in the state of diffused gas, which, however, gradually contracts, and consequently rises in temperature, and also rotates slowly. The rotation of the white-hot mass of gas causes it to assume a more or less spherical form. As the contraction goes on, the gas rotates faster and faster, and, because of the so-called "centrifugal force," throws off successive rings which condense to form planets, and these before they have cooled may similarly throw off whorls which become satellites. According to this theory, Neptune is the first-born, and Mercury the youngest child of the sun.

Dr. Roberts rightly remarks, in connection with his magnificent series of photographs of nebulæ, "These photographs throw a strong light on the probable truth of the *nebular hypothesis*, for they show what appears to be the progressive evolution of systems." We see the starting-point of a great system in the irregular nebula in Orion—that stage at which "the earth was without form and void, and darkness was upon the face of the deep." The great Andromeda nebula shows the next stage, in which rotation has caused the glowing gas to assume a regular outline, and to throw off luminous rings around the bright nucleus. The nebula in Canes Venatici represents a more advanced phase of the same process, with more rings and more masses undergoing condensation. Photographs of the nebulous stars in the Pleiades illustrate the next stage, in which the rings have disappeared, although traces of their gaseous matter are still visible around the bodies formed by them. Finally, in star clusters like Omega Centauri we see the process complete, and no trace of nebulosity left.

Some of the Applications of Celestial Photography.—In the course of this work we have repeatedly had occasion to describe applications of photography to astronomy. It may be well, therefore, to conclude by enumerating some of the chief features of what may with truth be called the New Astronomy:—

1. Photographs of the whole of the sun's surface are now daily taken at Greenwich, Paris, Potsdam, and other observatories, giving us a permanent record of the appearance of the sun from year to year, and of the periodical changes in the number and distribution of sun-spots.

In addition to these, large photographs showing the minute structure of the sun's surface (see Fig. 152, p. 291) have been taken by M. Janssen and others.

Also photography is now invaluable during eclipses of the sun for giving a permanent and reliable record of the appearance of the corona and prominences, and of the spectra of the sun's envelopes.

Within the last few years an ingenious method has been devised for photographing solar prominences even during full daylight, without having to wait for eclipses (see Figs. 158, 159, pp. 303, 304).

2. Photographs of the moon with an exposure of a minute or two show details of its surface which it would take years to accurately draw from telescopic observations. Some of the best photographs of the moon have been taken at Paris Observatory. Portions of the lunar surface are there photographed on a large scale, and by putting them together they give beautiful representations of the moon more than two yards in diameter. In these photographs details can be seen that the largest telescope fails to detect. On the plates, for example, lunar craters $\frac{1}{20}$ of a mile in diameter can be made out, although they are nearly a quarter of a million of miles from us!

3. Nearly every year several new planetoids are discovered from their trail on photographic plates (p. 329), and in 1898 a new planet was discovered between the earth and Mars by the same method.

4. Photographs of a comet show a far greater extent of the tail than telescopes reveal. They also show that the tail sometimes changes in appearance with a rapidity previously unknown, and they are modifying our former notions as to the regularly curved form of those cometary appendages (see p. 357).

5. Perhaps one of the most important applications of astronomical photography is the construction of the photographic star catalogue and star chart (see p. 370).

6. The applications of photography to the sidereal heavens are manifold. Plates exposed for a long time show apparently vacant portions of the sky to be crowded with stars. The width and density of the trails left by stars on stationary plates have proved one of the most rapid and reliable methods of determining the magnitudes of stars.

To find the distance of a star is one of the most delicate tasks in astronomy. By ordinary methods it, even in favourable cases, sometimes required years of observation. The photographic method (p. 266) introduced by the late Professor Pritchard of Oxford enables us, in the matter of a month, to tell the distances quite as accurately as by the instrumental methods.

By photographing the spectra of stars, we know much more about their movements and physical and chemical constitution than we did before.

7. Photographs of nebulæ have taught us much about their true shape and evolution. They have also led to the discovery of several new nebulæ, and have shown several others to be much more extensive than was previously supposed. Photographs show, for instance, that the Orion nebula is just the brightest part of a luminous haze involving practically the whole of the constellation. Similarly, the members of the Pleiades are involved in nebulosity which was not even suspected until it was revealed on photographic plates.

Other applications could be mentioned, but perhaps we have said enough to show how photography has in recent years not

only revolutionized all the old methods of astronomical observation, but has also made remarkable discoveries that could have been made by no other means. Mr. H. C. Russell, director of Sydney Observatory, suggests that in a few years the observer will have to stand aside while photography takes his place and works with a power of which he is not capable. The observer's work "will then be done by a new sensitive being, a being not subject to fatigue, to east winds, to temper, and to bias, but one above all these weaknesses, calm and unruffled, with all the world shut out, and living only to catch the fleeting rays of light and tell their story."

Questions.

1. What is meant by the "magnitude" of a star? How many stars of the sixth magnitude would be required to equal in brightness a single star of the first magnitude? Describe a method of determining the magnitudes of stars.

2. Why can more stars be photographed with a telescope than can be seen with a telescope?

3. Describe how the positions of the chief constellations and stars may be traced.

4. Give a brief account of the photographic star chart and star catalogue now being constructed. What will be the use and value of these?

5. How far is it correct to speak of the "fixed stars"? Mention the chief changes to which the position of a star is subject, and state in two or three lines the cause of each of them.

6. Describe briefly how the proper motions of the stars have been determined from observations made with the transit instrument.

7. Explain what is meant by the "proper motion of stars," and how it is distinguished from the common apparent motions.

8. How is it possible to calculate separately the aberration (the constant of aberration being supposed unknown), the annual parallax, and the proper motion of a star, from a long series of observations of the apparent place of a star?

9. What is meant by the proper motion of a star, and by a star's motion in the line of sight? How can the latter be measured?

10. What are the reasons for concluding that the sun has a proper motion through space?

11. Give an account of the various classes of variable stars, and the suggested causes of variability in each case.

12. When are stars termed *variable*? Give examples of such stars, and point out the causes which may give rise to the variability.

13. How have the phenomena of new and variable stars been explained?

14. What is a binary star? How can stars which are only optical doubles be distinguished from those which are physical doubles?

15. What are double stars? How has the physical connection of certain double or binary stars been found?

16. What is a star cluster, and how can a nebula be distinguished from a star cluster?

17. Describe various forms of nebulæ. State what is known concerning the nature of nebulæ.

18. Give an account of the application of photography to the study of nebulæ.

19. State the chief applications which are now made of photography in astronomical observations.

SPECIMEN EXAMINATION PAPERS.

BOARD OF EDUCATION, SECONDARY BRANCH, SOUTH KENSINGTON.

PHYSIOGRAPHY. ADVANCED STAGE.

GENERAL INSTRUCTIONS.

If the rules are not attended to, your paper will be cancelled.

Before commencing your work, you are required to fill up the numbered slip which is attached to the blank examination paper.

You may not have with you any books, notes, or scribbling paper.

You are not allowed to write or make any marks on your paper of questions, or to take it away before the close of the examination.

You must not, under any circumstances whatever, speak to or communicate with one another, and no explanation of the subject of examination may be asked or given.

You must remain seated until your paper has been collected, and then quietly leave the examination room. None of you will be allowed to leave before the expiration of one hour from the commencement of the examination, and no one can be re-admitted after having once left the room.

If any of you break any of these rules, or use any unfair means, you will be expelled, and your paper cancelled.

Before commencing your work, you must carefully read the following instructions:—

Candidates who have not applied to take the Elementary Stage may take the Advanced Stage, or Honours, but they must confine themselves to one of them.

Put the number of the question before the answer.

You are to confine your answers STRICTLY *to the questions proposed.*

The value attached to each question is shown in brackets after the question.

The examination in this subject lasts for three hours.

MAY, 1898.

You are permitted to answer SIX *questions. Of these, two must be taken from each series.*

First Series.

1. What is the nature of the movement in the solid crust of the globe which constitutes an earthquake? Give one or more illustrations of such movements. (40)

2. What is meant by the statement that water has a high specific heat? State how the temperatures of (*a*) the ocean, and (*b*) the atmosphere lying over the ocean, are affected by this property of water. (40)

3. What is the principle of the conservation of energy? Give a typical illustration of the transformation of energy. (40)

4. How would you determine the magnetic declination? What is known about the variations of this element? (40)

Second Series.

5. How is it that at different places on the shores of the British Islands the intervals between high water and low water vary, and that in some places we find we have four tides instead of two in the twenty-four hours? (30)

6. Why does the sun at the time of rising and setting appear to be (*a*) larger, (*b*) of a flattened or oval form, (*c*) with a different curvature below from that above, and (*d*) of a deep red colour? (30)

7. Describe one form of sunshine-recorder, and state how it is used. What are the chief causes which determine the amount of sunshine recorded at any place? (30)

8. What is a geyser? Describe the apparatus by which geyser action may be imitated, and explain its mode of working. (30)

Third Series.

9. Describe and illustrate by diagrams the thermal, illuminating, and photographic effects of the spectrum. (30)

10. Describe the telescopic appearance of the planet Venus. Why is this planet sometimes an evening and sometimes a morning star? (30)

11. What is meant by a variable star? What reasons have been suggested to account for the light-changes? Give two examples. (30)

12. How has the period of rotation of the sun been determined? State what facts you know concerning such determinations. (30)

May, 1899.

You are permitted to answer SIX *questions. Of these, two must be taken from each series.*

First Series.

1. Explain why a lightning-flash is seen before the thunder-peal is heard. Describe how you would determine the distance of a thunderstorm, giving an illustration. (40)

2. Why are clear nights generally cold ones? Explain the action of clouds in preventing the formation of hoar-frost. (40)

3. Describe *transverse* and *longitudinal* waves. Give an example of each. Describe *one* method of determining the velocity of light. (40)

4. Define *isogonic* and *isoclinic* lines, and describe how such lines are determined. (40)

Second Series.

5. State what you know concerning the variations in quantity of saline matter in different parts of the ocean. (30)

6. Describe an anticyclone, and state the direction of the movement of air in an anticyclone in the north hemisphere. State what are the indications of the barometer in different parts of an anticyclone. (30)

7. Give a sketch illustrating the mode of formation of springs. How does spring-water differ from rain-water, and why? (30)

8. Give examples of (*a*) a volcano subject to paroxysmal eruptions; (*b*) one in which the action is slight but constant; (*c*) one in which these two kinds of action alternate with one another. State what relations have been discovered between the duration of volcanic outbursts and the periods of rest between. (30)

Third Series.

9. Express clearly the meanings of *inferior conjunction*, *superior conjunction*, *opposition*, *elongation*, *quadrature*. Make a diagram in which all these terms are designated. (30)

10. Explain the causes which continually alter the direction of the earth's axis in space. (30)

11. Describe a typical sun-spot. State the reasons of their formation that have been suggested. At what parts of the solar disc are the spots fewest in number? (30)

12. Give an example of an aberration effect. Explain how the aberration of light alters the apparent positions of stars during a year. (30)

May, 1900.

You are permitted to answer SIX *questions. Of these, two must be taken from each series.*

First Series.

1. A tropical island is exposed to the heat of the sun all day, and to a clear sky at night. Describe and explain the movements in the atmosphere which result from these conditions. (40)

2. State what you know concerning—

(*a*) The variations in the temperature of the atmosphere as we pass upwards from the earth's surface;

(*b*) The variations in the temperature of the ocean as we pass downwards from its surface;

and explain the causes of the distribution of temperature in both cases. (40)

3. Describe an experimental method by which the velocity of light has been determined. State the value of this velocity. (40)

4. How is the position of a star defined in relation to the equatorial plane? Describe the method of determining *one* element of the position. (40)

Second Series.

5. Explain why the *apparent* times of sunrise and sunset are different from the true times. (30)

6. A thin layer of water in a porous dish is placed out-of-doors at night in India, and in the early morning is found to be converted into ice. Explain the causes by which this result is brought about. (30)

7. Assume that records of daily rainfall have been taken for ten years at a station. Explain how you would calculate the following :—

(*a*) The average annual rainfall of the place ;

(*b*) The average rainfall of each month of the year at that place ;

(*c*) The maximum and minimum rainfall for each month of the year at that place. (30)

8. Describe one form of horizontal pendulum used in seismological observations. (30)

Third Series.

9. What is a "meteor" or "shooting star"? Explain the cause of its luminosity. When are meteors most prevalent? (30)

10. How has the distance of the sun been determined by observations of Mars at opposition? (30)

11. Describe and explain the different appearances of the Saturnian system as seen from the Earth at various times. (30)

12. Name the magnetic elements, and describe how any two of them may be determined. (30)

Day Classes, June, 1898.

You are permitted to answer six *questions. Of these, not less than two, or more than three, must be taken from the first series, and one must be taken from the third series. The rest must be taken from the second series.*

First Series.

1. Explain the movements of a tidal wave—

(*a*) In the open ocean ;

(*b*) When it breaks on the shore. (40)

2. How is it, when the sun is shining brightly upon a mountain top, that the air may remain intensely cold? Why do the rocks on a mountain top, however much they may have been warmed during the day, quickly cool on a cloudless night? (40)

3. Explain what happens when felspar is acted upon by acid constituents of the atmosphere. (40)

4. How would you break white light up into its component colours? Describe an experiment which demonstrates that the red rays are not complex. (40)

Second Series.

5. Describe the methods of determining the depth of the ocean—

(*a*) By wire with detachable weight ;

(*b*) By Lord Kelvin's (Sir William Thomson's) tubes. (30)

6. How are fogs produced? Why are fogs most prevalent—

(*a*) In river valleys ;

(*b*) Over great cities? (30)

7. Describe the apparatus and method of procedure employed in determining the mean annual rainfall of a place. State the special precautions which must be taken in making rainfall observations. (30)

8. Describe the internal structure of a volcanic cinder- (scoria-) cone. Describe a piece of apparatus by which the building up of such cones may be imitated. (30)

9. Describe what the phenomena of day and night would be, supposing the plane of the earth's equator to be at right angles to the plane of the ecliptic. (30)

10. What is the constant of aberration? How can the distance of the sun be determined by its means? (30)

11. What is meant by the equation of time? Define the "mean sun," and state why it is that mean and apparent solar time sometimes coincide. (30)

12. What is meant by the periodicity of sun-spots? State what relationship exists between their position on the sun's disc and their frequency, and give numbers. (30)

Third Series.

13. Give notes of a lesson, to a class of children, on solar time, and sidereal time, explaining the illustrations you would employ to make the matter clear. (40)

14. How would you explain to your class the physical causes which make a sojourn at the seaside so pleasant at the hottest season of the year? (40)

15. How would you explain to a class of children the meaning of the charts constructed to illustrate the distribution of barometric pressure over the British Islands? Include in your explanation the sources of the data on which these charts are constructed and the nature of the deductions in the way of weather forecasts that can be made from them. (40)

Day Classes, June, 1899.

You are permitted to answer SIX *questions. Of these, not less than two, or more than three, must be taken from the first series, and one must be taken from the third series. The rest must be taken from the second series.*

First Series.

1. Why is the sun seen above the horizon for some minutes after it has actually set? Explain the phenomenon by the aid of a diagram. (40)

2. Explain how it is that the water in a vessel of porous earthenware remains cool in the warmest weather. (40)

3. Describe a simple pendulum, and state the law connecting the time of oscillation with its length. Explain why it is that for a pendulum of given length the time of oscillation varies at different places on the earth's surface. (40)

4. Describe fully one experimental determination of the mechanical equivalent of heat. (40)

Second Series.

5. What is meant by "regelation"? Describe a simple experiment to illustrate regelation. (30)

6. Explain exactly what is meant by "gradients" in statements of the distribution of atmospheric pressure. (30)

7. What is a landslip? State the causes to which landslips are generally due. (30)

8. Explain the modes of formation of—
   (*a*) Parasitical volcanic cones;
   (*b*) Crater-lakes;
   (*c*) Caves and tunnels in lava-streams. (30)

9. What is meant by the precession of the equinoxes? Give its yearly value in seconds of arc. Describe generally the method usually employed to ascertain it. (30)

10. Describe the general appearance of a large comet as it approaches the sun. How do the orbits of comets differ from those of planets? (30)

11. Explain the reasons for the differences of the apparent paths of sun-spots at different times of the year. Draw a diagram to illustrate the apparent paths for March, June, September, and December. (30)

12. Describe Foucault's gyroscope, and explain how it was employed to determine the time of rotation of the earth. (30)

Third Series.

13. Explain to a class of children the sun-dial, its use, and why the time given by it differs from "mean time" as shown by a clock. (40)

14. Give notes to a class of children on the mode of formation of rainbows. (40)

15. Explain to a class of children the phenomena of thunderstorms, and the causes by which they are produced. How would you refer to the subject of "thunderbolts"? (40)

Day Classes, June, 1900.

You are permitted to answer SIX *questions. Of these, not less than two, or more than three, must be taken from the first series, and one must be taken from the third series. The rest must be taken from the second series.*

First Series.

1. Describe two experiments by which you could illustrate—
   (*a*) The wind theory of ocean currents;
   (*b*) The convection theory of ocean currents. (40)

2. How is it that on a high mountain, even when the sun is shining brightly, the air may be intensely cold? (40)

3. Define diurnal, annual, and horizontal parallax. Give drawings illustrating each. (40)

4. Name and illustrate by diagrams the elements of a planet's orbit. What are the chief differences between cometary and planetary orbits? (40)

Second Series.

5. State the conditions necessary for the formation of rainbows. Under what circumstances may a rainbow form a complete circle, and why is only a portion of the circle seen in ordinary cases? (30)

6. What is meant by "hard" and "soft" water? Describe and explain a process by which hard water may be softened. (30)

7. Give an account of the chief characters presented by snowflakes. How do you explain these characters? (30)

8. Describe the chief features presented by lava-streams. (30)

9. Describe the development and direction of comets' tails as they move round the sun. What is the explanation suggested to account for multiple tails? (30)

10. How does the knowledge of the velocity of light and the constant of aberration help us in determining the distance of the earth from the sun? (30)

11. Give a statement of the differences between the surface markings of Jupiter and Mars. (30)

12. What is meant by the "obliquity of the ecliptic"? State what is known about its variation, and describe the effects produced on the apparent position of a star. (30)

Third Series.

13. Explain, as to a class of children, the causes of the phases of the moon. (40)

14. Show the construction of a barometer, as to a class of children, explaining every step taken, and the reason for each. (40)

15. Give notes of a lesson on the depth of the ocean, and the manner in which it is determined. (40)

May, 1901.

You are permitted to answer SIX *questions. Of these, two must be taken from each series.*

First Series.

1. What liquids, other than mercury, have sometimes been employed in the construction of barometers? What are the chief objections to their use? (40)

2. Describe the differences between a snowflake and a hailstone, and explain the conditions under which each is formed. (40)

3. Describe the appearances seen on the sun's surface from time to time. How do these help us to determine the period of rotation of the sun? State the length of this period. (40)

4. Explain clearly the cause of "nutation," and describe and illustrate the effect of this motion on the position of the pole star. (40)

Second Series.

5. What are the monsoons, and how are they produced? (30)

6. What is meant by the statement that anticyclonic conditions prevail at a certain place? What kind of weather usually accompanies those conditions? (30)

7. Explain how vessels containing mercury have been employed to reveal and register earth-movements. (30)

8. Describe the exact methods by which the nature of glacier-movement and its rate have been determined. (30)

THIRD SERIES.

9. Describe the "eclipse" theory and the "meteoritic" theory of variable stars, and give examples of each. (30)

10. What are the reasons which lead us to conclude that the moon has little or no atmosphere? (30)

11. What is meant by the magnetic "variation" or "declination"? Describe the changes that occur in this element at any one place. (30)

12. Define the "proper motion" of a star, and state how large proper motions help us to determine the distances of the stars. (30)

ANSWERS.

Chapter I.

11. Young's modulus $= \frac{WL}{A\ell}$

$$\therefore \ell = \frac{WL}{A \times \text{Young's modulus}}$$

$$= \frac{85 \times 15 \times 12}{0{\cdot}01 \times 17000000} \text{ inch}$$

$$= \mathbf{0{\cdot}09 \text{ inch.}}$$

Chapter II.

4. Work done per minute $= 200 \times 30 \times \frac{6}{8}$ foot-pounds

$$\therefore \text{rate of doing work} = \frac{200 \times 30 \times 60}{8 \times 33000} \text{ H.P.}$$

$$= \mathbf{1\frac{4}{11} \text{ H.P.}}$$

5. Work done in $1\frac{1}{4}$ minute $= 220 \times 30$ foot-pounds,
or $220 \times 30 \times g$ foot-poundals

$\therefore$ (*a*) Work done per minute $= \frac{220 \times 30}{1\frac{1}{4}}$ foot-pounds

$$= \mathbf{5280 \text{ foot-pounds.}}$$

(*b*) Work done per second $= \frac{220 \times 30 \times g}{1\frac{1}{4} \times 60}$ foot-poundals

$$= \mathbf{2816 \text{ foot-poundals.}}$$

(*c*) Rate of doing work $= \frac{5280}{33000}$ H.P.

$$= \mathbf{\frac{4}{25} \text{ H.P.}}$$

7. Velocity of locomotive $= 88$ feet per second

$\therefore$ (*a*) Kinetic energy of locomotive $= \frac{1}{2}MV^2$ foot-poundals

$$= \frac{1}{2} \times 80 \times 2240 \times 88 \times 88 \text{ foot-poundals}$$

$$= \mathbf{693,862,400 \text{ foot-poundals.}}$$

$\therefore$ (*b*) Kinetic energy of locomotive $= \frac{693862400}{32}$ foot-pounds

$$= \mathbf{21,683,200 \text{ foot-pounds.}}$$

12. $t_1 : t_2 = \sqrt{l_1} : \sqrt{l_2}$

$$= \sqrt{36} : \sqrt{18}$$

$$= \mathbf{\sqrt{2} : 1.}$$

15. Time for one oscillation $= \frac{5}{807}$ minute $= \frac{300}{807}$ second.

$$\text{Now } g = \frac{\pi^2 l}{t^2}$$
$$= \frac{9{\cdot}87 \times 13{\cdot}7}{\frac{300^2}{807^2}}$$
$$= \frac{88061238{\cdot}531}{90000}$$
$$= \mathbf{978{\cdot}46 \text{ cms. per second per second.}}$$

16. $1^2 : (\frac{1}{2})^2 :: 39{\cdot}2$ inches : length
whence length $= \mathbf{9{\cdot}8 \text{ inches.}}$

Chapter III.

14. (*a*) Quantity of heat required = specific heat × mass × rise of temperature
$= 0{\cdot}031 \times 1000 \times 10$
$= \mathbf{310 \text{ calories.}}$

(*b*) ,, ,, ,, $= 1 \times 1000 \times 10$
$= \mathbf{10{,}000 \text{ calories.}}$

15. Let t stand for the final temperature. Then since
Heat lost by warm water = heat gained by cold water and calorimeter
$\therefore 150(98 - t) = (250 + 30{\cdot}32 \times 0{\cdot}095)(t - 15)$
whence $t = \mathbf{45°{\cdot}9 \text{ C.}}$

16. (*a*) Heat lost on cooling = specific heat × mass × fall of temperature
$\therefore 44{\cdot}96 =$ specific heat $\times 5 \times 80$
whence specific heat $= \mathbf{0{\cdot}1124.}$

(*b*) Quantity of heat required = specific heat × mass × rise of temperature
$= 0{\cdot}1124 \times 25 \times 30$
$= \mathbf{84{\cdot}3 \text{ calories.}}$

17. Heat lost by iron = heat gained by water
$\therefore$ specific heat $\times 12 \times (100 - 33) = 1 \times 5 \times (33 - 15)$
whence specific heat $= \mathbf{0{\cdot}112 \text{ nearly.}}$

Chapter IV.

10. $v = l \times n$
$\therefore 1100 = 4 \times n$
whence $n = \mathbf{275 \text{ per second.}}$

12. Velocity of sound in air at 0° C. is 1086 feet per second
$\therefore$ velocity of sound at 30° C. $= 1086 + 60$
$= 1146$ feet per second
$\therefore$ distance of lightning $= 1146 \times 7$ feet
$= \mathbf{8022 \text{ feet.}}$

Chapter V.

20. So long as the iron is at a black heat there are only infra-red vibrations. When the iron is red-hot (at a temperature of about 500° C.) the red part of the spectrum appears. At still higher temperatures the orange, yellow, etc., are added in succession, until at last, when the iron is white-hot, we get the complete spectrum. At still higher temperatures the ultra-violet spectrum may make its appearance.

Chapter VIII.

9. The difference of the readings is 14 hundredths of an inch in 34 miles, or 7 hundredths in 17 miles; therefore the gradient is **7**.

10. The difference of the readings was 1·76 inch, or 176 hundredths of an inch, in 673 miles: what was the difference in 17 miles?

$$673 : 17 :: 176 : x = 4{\cdot}45 \text{ hundredths of an inch}$$

therefore the barometric gradient was **4·45**.

Chapter XVI

20. Let D represent the distance of earth from sun, and x the distance of asteroid from sun. Then—

$$1^2 : 27^2 :: D^3 : x^3$$
$$\therefore x^3 = 27^2 \times D^3$$
$$= 729D^3$$
$$= 9^3D^3$$
$$\therefore x = 9D.$$

23. (*a*) **92,819,250 million miles.**
(*b*) **928,192,500** ,, ,,

26. Distance of sun $= \dfrac{206265 \times 3960}{8{\cdot}8}$ miles

$$\therefore \text{diameter of sun} = \frac{\frac{206265 \times 3960}{8{\cdot}8} \times 1920}{206265} \text{ miles}$$
$$= \mathbf{864{,}000 \text{ miles.}}$$

Chapter XIX.

11. $$\frac{1}{E} - \frac{1}{P} = \frac{1}{S}$$
$$\frac{1}{1} - \frac{1}{30} = \frac{1}{S}$$
$$\therefore S = 1\tfrac{1}{29} \text{ year.}$$

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